Volume XLIII September-October 1948 Number 6

Economic Geology

and the

Bulletin of the Society of Economic Geologists

OCT 12 1948

CONTENTS

Tin-Silver Veins of Oruro, Bolivia (Part II) ..... *Fred M. Chace* 435

Ore and Granitization ..... *C. J. Sullivan* 471

Metamorphic Gradient, Kent Coalfield, England ..... *H. W. Wellman* 499

The Bedding Replacement Fluorspar Deposits of Spar Valley, Eagle Mountains, Hudspeth County, Texas ..... *Elliot Gillerman* 509

Distribution of Coastal Black-sands in North Carolina, South Carolina, and Georgia, as Mapped from an Airplane ..... *V. E. McKelvey and J. R. Balsley, Jr.* 518

Discussion and Communications:

Mineral Relationships in the Ores of Pachuca and Real del Monte, Hidalgo, Mexico ..... *Edson S. Bastin* 525

Reviews:

Geological Structures and Maps (Roberts) 526

Louis Agassiz, Scientist and Teacher (Teller) 526

Petrography and Petrology of South African Clays (Bosazza) 526

Handbook of Chemistry and Physics, 30th Edit. (Hodgman) 526

Mineral Resources of Colorado (Vanderwilt) 527

Books Received ..... *Alan T. Broderick* 527

Scientific Notes and News 531

PUBLISHED SEMI-QUARTERLY

Five Dollars a Year, One Dollar a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

Issued Semi-Quarterly and sent to subscribers on or about the following dates: February 1, March 15, May 1, June 15, August 1, September 15, November 1, December 15.

Manuscripts for publication should be sent to the Editor, **ALAN M. BATEMAN, at Yale University, Yale Station, New Haven, Conn.** It is requested that contributors exercise care in writing *scientific* and *proper names*. References to other publications should be in accordance with the forms used in the pages of this journal. The manuscript should be typewritten with double space lines and must be preceded by *a brief abstract*. Galley proof will be sent authors only where a request to this effect accompanies the manuscript, or when, in the editor's opinion, the subject matter is such as will require correction by the author.

Reviews should conform to the journal usage. Review Committee: The Editor, C. H. Behre, L. C. Graton, J. T. Singewald, Jr., J. Gilluly, A. F. Buddington, W. H. Newhouse.

Books and Pamphlets for review should be sent to the Editor.

Reprints. Contributors desiring reprints of their papers may obtain them by filling out the order slip which will be attached to the galley proof when it is sent to the author. Provided the order slip is received by the editor, *with the return of the proof*, 50 reprints without covers will be furnished without charge. Reprints of discussions and informal communications are not furnished free of charge except when they exceed four pages in length when 50 will be supplied without charge. Reprints of reviews are not supplied. Additional reprints will be furnished at approximately the rates given in the table below when ordered *in advance of publication*. The rates apply only to plain text, with line engravings. Papers containing folded maps or plates will be more expensive.

The following rates *do not* include free carriage. *Postage or express must be paid by the author.*

	4 pp. 1–4	8 pp. 5–8	12 pp. 9–12	16 pp. 13–16	20 pp. 17–20	24 pp. 21–24	28 pp. 25–28	32 pp. 29–32
50 copies.....	$2.75	$4.40	$6.87	$7.15	$ 9.35	$10.72	$12.37	$13.20
100 "	3.30	5.22	7.97	8.80	11.27	13.20	15.40	16.50
Additional copies per C.	1.10	1.65	2.75	3.30	3.85	4.95	6.05	6.60

For 500 copies deduct 5%; for 1000 copies or more deduct 10%. For more than 32 pages add cost per schedule to make total. Example: For 44 pages add cost for 32 pages and 12 pages. The 50 copy price is the minimum charge.

Covers: For first 50 covers, $3.80; additional 2½¢ each. Standard covers are of the same style of type and paper as the cover of the journal, and bear the title of the article and name of its author. Special printing on cover is charged for at the cost of composition.

Plates are $2.70 for the first 50 if printed on one side, and 2 cents for additional ones; printed on both sides, $4.05 for the first 50, and 3 cents for additional ones.

Note: For any reprints requiring additional composition or changes, either in text or cover, an extra charge will be made.

Single copies of reprints (without covers) of many of the articles published in volumes issued since 1926 (Vol. XXI) are available at the following prices, upon application to the Business Editor, at Urabana, Illinois.

1–4 pp. 15c	5–8 pp. 20c	9–12 pp. 25c	13–20 pp. 30c	21–28 pp. 35c
29–36 pp. 40c	37–44 pp. 45c	45–52 pp. 50c	53–60 pp. 55c	61–68 pp. 60c

Subscriptions. The price of the journal to subscribers in the United States and its dependencies is $1.00 for a single copy, or $5.00 a year for eight numbers. To subscribers in Canada, Cuba, Mexico, Spain, and countries in Central and South America, except Dutch and French Guiana, the annual rate is $5.30; to other countries, $5.75.

Forwarding. Subscribers wishing their journal to be forwarded to a new address should leave postage for that purpose with the Postmaster at their old address.

Missing numbers will be replaced without charge if claim is made within four weeks after the date of issue of the following number, provided that the neglect to receive them is not due to neglect to arrange for their forwarding.

Remittances should be made payable to the **ECONOMIC GEOLOGY PUBLISHING COMPANY,** and should be mailed to **M. M. LEIGHTON,** Business Manager, Urbana, Illinois, to whom also all **Business Communications** should be addressed.

Foreign Agents. Geo. Allen and Unwin, Ltd., No. 40 Museum St., London, W. C. 1, British Agents.

Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF ECONOMIC GEOLOGISTS

OCT 12 1948
MANHATTAN

EDITOR: ALAN MARA BATEMAN
Yale University, New Haven, Connecticut

BUSINESS EDITOR: MORRIS M. LEIGHTON
Illinois Geological Survey, Urbana, Illinois

ASSOCIATE EDITORS

CHARLES KENNETH LEITH
University of Wisconsin, Madison, Wis.

D. F. HEWETT
U. S. Geological Survey, Washington, D. C.

C. N. FENNER
Geophysical Laboratory, Washington, D. C.

B. S. BUTLER
Univ. of Arizona, Tucson, Ariz.

W. E. WRATHER
U. S. Geological Survey, Washington, D. C.

HEINRICH RIES
Cornell University, Ithaca, N. Y.

L. C. GRATON
Harvard University, Cambridge, Mass.

E. S. MOORE
University of Toronto, Toronto, Can.

A. I. LEVORSEN
Department of Geology, Stanford University, Calif.

PER GEIJER
Geological Survey of Sweden, Stockholm, Sweden

P. F. FOURMARIER
Liège, University, Liège, Belgium

M. J. S. KRISHNAN
Geological Survey, Calcutta, India

DJALMA GUIMARÃES
Instituto de Tecnologia Industrial Belo Horizonte, Minas Gerais, Brazil

A SEMI-QUARTERLY JOURNAL PUBLISHED BY
THE ECONOMIC GEOLOGY PUBLISHING COMPANY

SOCIETY OF ECONOMIC GEOLOGISTS

THE PUBLICATIONS OF WHICH CONSTITUTE
A PART OF THIS JOURNAL

OFFICERS FOR 1948

T. M. BRODERICK .....*President*
T. B. NOLAN .....*President elect*
OLAF N. ROVE .....*Secretary*
Annandale Road, R. F. D. No. 1
Falls Church, Va.

SIDNEY PAIGE .....*Vice-Pres.*
HUGH MCKINSTRY ...*Vice-Pres. elect*
JOSEPH T. SINGEWALD, JR...*Treasurer*
Johns Hopkins Univ., Baltimore, Md.

Councilors

1948	*1949*	*1950*
V. T. STRINGFIELD	ERNEST F. BEAN	CARLTON D. HULIN
FRANK R. CLARK	GILBERT H. CADY	DONALD DAVIDSON
JOSEPH L. GILLSON	J. E. HAWLEY	WILLIAM CALLAHAN

Regional Vice-Presidents

DAVID WILLIAMS .....London, England .....*For Europe*
P. K. GHOSH .....Calcutta, India .....*For Asia*
HENDRICK JAN SCHUILING ..Jadotville, Belgian Congo .....*For Africa*
W. F. JAMES .....Toronto, Ont. .....*For North America*
VICTOR LOPEZ .....Caracas, Venezuela .....*For South America*
H. G. RAGGATT .....Canberra City, Australia .....*For Australia*

Executive Committee

T. M. BRODERICK, *Chairman* — SIDNEY PAIGE — T. B. NOLAN
OLAF N. ROVE — JOSEPH T. SINGEWALD, JR. — GEORGE H. ASHLEY

Finance Committee

W. H. CALLAHAN, *Chairman* — JOSEPH T. SINGEWALD, JR. — GEORGE C. HEIKES
WILLIAM O. HOTCHKISS

Program Committee

C. F. PARK, JR., *Chairman* — C. O. SWANSON — OLAF N. ROVE
M. L. BRASHEARS, JR. — A. W. STICKNEY — L. H. HART

Committee on Publications

H. E. MCKINSTRY, *Chairman* — J. E. HAWLEY — R. E. GRIM

Nominating Committee

D. M. DAVIDSON, *Chairman* — GEORGE W. BAIN — W. L. WHITEHEAD

Admissions Committee

V. T. STRINGFIELD, *Chairman* — ELDRED D. WILSON
WILLIAM B. HEROY — JAMES NOBLE — PHILIP J. SHENON

LIBRARY
OCT 12 1948
MANHATTAN

ECONOMIC GEOLOGY

AND THE

BULLETIN OF THE SOCIETY OF
ECONOMIC GEOLOGISTS

VOL. XLIII SEPTEMBER–OCTOBER, 1948 No. 6

TIN–SILVER VEINS OF ORURO BOLIVIA.

F. M. CHACE.

PART II.

CONTENTS—PART II.

PAGE
Rock alteration 435
Vein mineralogy 439
Genesis of the Oruro ore deposit 457

ROCK ALTERATION.

THE rock alteration associated with ore deposition at Oruro varies considerably in intensity with the several rocks affected, and in the quartz latite porphyry there is a distinct gradation of alteration with the distance from the channelways along which ore was deposited. Three phases of alteration may be distinguished in the igneous rocks, as follows:

1. A widespread but relatively slight development of sericite in all of the igneous rocks of the region. Chlorite was formed in a few localities.
2. A moderate phase within the stocks in the area of mineralization resulting in sericite and pyrite, and obliteration of chlorite, but without destroying the original texture of the rock.
3. An intense phase close to the veins, in which the rock is converted to an aggregate of sericite, pyrite, and a small amount of alunite, with nearly complete destruction of the original texture. Locally tourmaline was formed.

The products of wall-rock alteration are most abundantly developed in the igneous rocks. The Oruro formation has been little affected by hydrothermal solutions except close to veins. The San José breccia is always altered in varying degrees, but it is difficult to determine how much of the alteration is due to late hydrothermal attack during the period of mineralization.

Alteration of the Igneous Rocks—Feeble Phase.—All of the igneous rocks from San Pedro and Viscachani mountains far removed from the veins contain some sericite and chlorite. In the hand specimen, such rocks generally

appear fresh, and feldspar, biotite and quartz are readily identified, but close inspection with a hand lens reveals that the individual minerals are somewhat clouded with alteration products.

Under the microscope, sericite, calcite, chlorite, serpentine, and hematite are found. Clusters and tiny flakes of sericite are scattered through the plagioclase phenocrysts along cracks and twinning planes in the crystals. In the zoned plagioclase crystals, sericite is developed in the more calcic bands, leaving the others relatively unattacked. The sericite, however, is never in sufficient abundance to obliterate the twinning or the shape of the mineral grains or to make identification uncertain. Commonly, traces of calcite are associated with the sericite in the plagioclase. This suggests that in the breakdown of the feldspars the potassium and aluminum were incorporated in the sericite and the calcium was liberated to form calcite.

Chlorite, formed largely at the expense of biotite, is erratically distributed. Locally, the biotite is completely altered; elsewhere, it may be quite fresh. Biotite, partially replaced by hematite, is rather common. Near the surface the hematite breaks down to limonite.

Scattered grains of pyroxene or amphibole are altered pseudomorphically in all cases to chlorite and serpentine. The outlines of the original crystals are well preserved, but the degree of alteration is so intense that exact identity of the mineral is uncertain.

The groundmass of the quartz latite porphyry is usually fairly fresh, though patches of chlorite, sericite, and kaolin are common in it. Kaolin rims around the deeply embayed quartz grains are numerous. In this case, the kaolin was probably formed by surface oxidation.

Figure 35 shows the characteristic alteration products of the feebly altered zone.

Moderate Phase.—In a sense there is a sharp break between the feeble alteration and the moderate alteration. All the igneous rocks away from the mines were affected by the feeble phase, whereas the quartz latite porphyry bodies associated with the veins were altered by the moderate phase throughout their entire extent. The difference between the feeble and the moderate phases is one of degree rather than of kind, for the same products are present. However, there are several minor differences worthy of record.

The moderate alteration consists of the development of sericite and pyrite on an extensive scale. In fact, few specimens of quartz latite porphyry can be found in the San José mine even far from veins without disseminated pyrite. The moderately altered porphyry is a light-gray rock with pinkish-white to white feldspar phenocrysts.

Microscopically, the alteration products are found to be sericite and pyrite. Chlorite of the feeble phase has been largely destroyed. Only traces of the chlorite are found replaced by sericite. The plagioclase is replaced by sericite and in many cases only outlines of the original minerals remain. Where the change is less intense, albite twinning remains, and the mineral is identifiable as andesine. Pyrite is abundant in tiny cubes, octahedrons, and irregular grains varying from pin points to two millimeters across. It replaces all of the rock minerals, including phenocrysts and matrix alike.

The pyroxene and amphibole have nearly disappeared, leaving mattes of sericite and a trace of chlorite and calcite. The matrix is fresh in places, but generally it is replaced by sericite. Secondary quartz in fine grains is found in the moderately altered zone, but is not common.

Figure 36 shows the general features of the intermediate phase of alteration.

Intense Phase.—Adjacent to the veins, the quartz latite porphyry has been completely altered to gray or white masses of quartz, sericite, kaolin (dickite) and pyrite. The original porphyritic texture of the rock has been entirely obliterated, and the rock is a dense, fine-grained intergrowth with scattered vitreous quartz phenocrysts preserved from the original rock and unchanged by hydrothermal solutions even at the vein. The width of the intensely altered zone is seldom over one meter and in places it is only 10 centimeters. It is gradational into the moderately altered zone, and rarely can a sharp boundary be found. Despite the intensity and completeness of the changes they have undergone, the original texture of these rocks is remarkably well preserved throughout all stages of alteration. Only in the few centimeters nearest a vein do the rocks lose their texture entirely.

Under the microscope, the intensely altered rock proves to be a textureless intergrowth of quartz and sericite. Coarse euhedral to irregular grains of pyrite, usually much larger than the other constituents, are disseminated through the rock and in places coalesce to form veins and irregular patches of solid sulphide.

Traces of plagioclase remain replaced pseudomorphically by mattes of sericite. Where alteration is most intense, not even the feldspar outlines remain, and secondary quartz has partially replaced sericite. Silicification is the most important process of this zone. Tiny grains of quartz replace the groundmass, and occur as the residue of phenocrysts and in veinlets traversing the rock. No traces of the biotite or chlorite remain. The quartz phenocrysts alone maintain their original features. In many cases, round quartz grains have rims of kaolin and sericite a fraction of a millimeter wide. Alunite and dickite are found in the wall rock adjacent to the veins, but nowhere are they abundant.

Figure 37 illustrates the characteristic alteration of the intensely altered zone.

Tourmaline.—In addition to sericite, pyrite, and quartz, minerals characteristic of both the moderate and intense phases of wall-rock alteration, tourmaline has been noted by Kozlowski and Jaskolski,[36] Ahlfeld,[37] and Campbell,[38] in the wall rocks adjacent to the Oruro veins, particularly in the Itos mine. Ahlfeld described some of the rock on the lower mine levels as so intensely tourmalinized that it is nearly greisen. The other authors, however, observe that the mineral is very scarce. Lindgren[39] found radiating

[36] Kozlowski, R. and Jaskolski, S., Les gisements argento-stannifères d'Oruro en Bolivie: Arch. Min. Soc. Sci. Var., vol. 8, pp. 1–100, 1932.

[37] Ahlfeld, Federico, Los yacimientos minerales de Bolivia, La Paz, Bolivia, January 1941.

[38] Campbell, Donald F., op. cit.

[39] Lindgren, W. and Abbott, A. C., The silver-tin deposits of Oruro, Bolivia: ECON. GEOL., vol. 26, no. 5, pp. 453–479, 1931.

groups of minute, colorless needles which "proved difficult to identify" replacing feldspar in the wall rock. He suggested that the mineral may be tourmaline, but said that "definite identification is still in abeyance."

Careful search of many thin sections of wall rock and ore failed to reveal the presence of tourmaline in the author's collection. Possibly these authors may have mistaken "needle cassiterite" for tourmaline, for it is rather common. On the other hand, it may well be that the author's collection from certain areas, such as the bottom levels of the Itos mine, is not sufficiently extensive and inadvertently missed the rock containing tourmaline.

The presence of tourmaline in the wall rock adjacent to the Oruro veins, although in small amounts and only in localized places, has considerable significance, for it is generally interpreted as indicating high-temperature conditions during formation. The significance of the mineral, therefore, will be considered in more detail in the chapter on ore genesis. In this connection it is important to note that tourmaline is very abundant at Llallagua. Turneaure [40] found that colorless tourmaline occurs in nearly every thin section of the altered porphyry, clastic dikes and breccias of that district.

Alteration of the San José Breccia.—The San José breccia is altered everywhere. The changes are similar to those of the intensely altered phase of the quartz latite porphyry, and, in general, the degree of alteration increases toward the veins. The widespread extent of intense alteration in the breccia may be due in part to its greater permeability, but it is not unlikely that some of the changes took place during its formation when solutions somewhat similar to, if not the same as, hydrothermal solutions were present. The changes accompanying the circulation of orebearing solutions were superimposed on the original alteration, as indicated by the increase in intensity of alteration as the veins are approached.

The products of rock alteration are particularly well developed in the porphyry fragments of the breccia, although similar minerals replace the argillite fragments and matrix to a lesser extent. The porphyry fragments maintain their outlines throughout the stages of alteration, but the minerals are nearly completely obliterated. The feldspar phenocrysts are always altered to an aggregate of sericite, and as the veins are approached lose their identity in outline. The matrix is altered to sericite and kaolin, but its black color is preserved even close to the veins. Secondary quartz is found in traces far from veins replacing matrix and porphyry fragments and increases in amount toward the channelways. However, the rock never becomes completely silicified. Pyrite is widely distributed throughout the breccia and replaces porphyry, argillite, and matrix, but it shows a decided preference for the porphyry. The fragments of igneous rock are commonly peppered with fine grains of disseminated pyrite. As does the quartz, pyrite increases in amount as the veins are approached and is found in numerous veinlets as well as disseminated grains. Close to the veins alunite is found in small amounts (Figs. 38, 21).

[40] Turneaure, F. S., The tin deposits of Llallagua, Bolivia: ECON. GEOL., vol. 30, pp. 14–60, 170–190, 1935.

Alteration of the Oruro Formation.—The Oruro formation is not altered except close to the veins. This is due probably to the absence of cracks, joints, and through-going fractures, and to its low permeability. However, in some places pyrite is fairly abundant in disseminated grains, but more commonly in reticulating veinlets and tiny manto veins parallel to the argillite bedding.

Close to the veins, pyrite, quartz, and secondary sericite have developed in the argillite. The minerals usually are not disseminated through the rock replacing original constituents, but rather are in many small replacement veins, forming a complicated network.

VEIN MINERALOGY.

A large number of minerals have been found in the Oruro district, but many of them are rare or have been observed only with the microscope. The following lists are made up of those minerals observed by the writer, plus the less abundant ones reported by Lindgren,[41] Kozlowski and Jaskolski,[42] Stelzner,[43] and Spencer [44].

Vein mineralization at Oruro took place in three stages, two of which were hypogene, resulting in the formation of the primary ores, and the third, supergene, whereby the oxidized or "pacos" ores were formed. The stages of mineralization, recognized and divided on the basis of vein structure, mineralogy, and textures, are as follows:

1. Quartz-pyrite-cassiterite stage.
2. Silver sulphosalt stage.
3. Oxidized or pacos ore stage.

ORE MINERALS OF THE HYPOGENE STAGE.

Andorite	— $PbAgSb_3S_6$	Miargyrite	— $AgSbS_2$
Arsenopyrite	— $FeAsS$	Plagionite	— $Pb_5Sb_8S_{17}$
Boulangerite	— $Pb_5Sb_4S_{11}$	Pyrite	— FeS_2
Bournonite	— $PbCuSbS_3$	Pyrrhotite	— $Fe_{1-x}S$
Cassiterite	—SnO_2	Ruby silver	— Ag_3SbS_3
Chalcopyrite	— $Cu_2Fe_2S_4$	Semseyite	— $Pb_9Sb_8S_{21}$
Chalcostibite	— $CuSbS_2$	Sphalerite	— ZnS
Franckeite	— $Pb_5Sn_2Sb_2S_{14}$	Stannite	— Cu_2FeSnS_4
Freieslebenite	— $Pb_2Ag_2Sb_4S_{12}$	Stephanite	— Ag_5SbS_4
Galena	— PbS	Stibnite	— Sb_2S_3
Hematite	— Fe_2O_3	Tetrahedrite (freibergite)	— $(Cu, Fe)_{12}Sb_4S_{13}$
Jamesonite	— $Pb_4FeSb_6S_{14}$	Wolframite	— $(Fe, Mn)WO_4$
Marcasite	— FeS_2	Wurtzite	— ZnS
Meneghinite	— $Pb_{13}Sb_7S_{23}$	Zinkenite	— $Pb_9Sb_{14}S_{27}$

[41] Lindgren, W. and Abbott, A. C., op. cit.

[42] Kozlowski, R. and Jaskolski, S., op. cit.

[43] Stelzner, A. W., Die silber-zinnlagerstatten, Bolivias: Zeit dd. Geol. Ges., vol. 49, pp. 51–142, 1897; also, Bemerkungen über zinckenite von Oruro in Bolivia: Zeit. Krist. u. Min. 24, p. 126, 1895.

[44] Spencer, L. J. (Analyses, J. T. Prior), Crystallized stannite from Bolivia: Mineral. Mag., vol. 13, p. 54, 1901; also Krystallisirter zinnkies von Bolivia: Zeit. Krist. u. Min. 35, p. 475, 1902; also Notes on some Bolivian minerals: Mineral. Mag., vol. 14, pp. 308–344, 1907.

GANGUE MINERALS.

Alunite	— $K_2Al_6(OH)_{12}(SO_4)_4$	Quartz	— SiO_2
Apatite	— $(CaF)Ca_4(PO_4)_3$	Sericite	— (H, K)$AlSiO_4$
Augelite	— $2Al_2O_3.P_2O_5.3H_2O$	Siderite	— $FeCO_3$
Barite	— $BaSO_4$	Tourmaline	— $H_9Al_2(B.OH)_2Si_4O_{19}$
Kaolinite	— $H_4Al_2Si_2O_9$	Wavellite	— $4AlPO_4.2Al(OH)_3.9H_2O$

OXIDIZED ZONE MINERALS.

Anglesite	— $PbSO_4$	Jarosite	— $K_2Fe_6(OH)_{12}(SO_4)_4$
Cerargyrite	— AgCl	Limonite	— $2Fe_2O_3.3H_2O$
Cerussite	— $PbCO_3$	Marcasite	— FeS_2
Cervantite	— $Sb_2O_3.Sb_2O_5$	Melanterite	— $FeSO_4.7H_2O$
Covellite	— CuS	Metastibnite	— Sb_2S_3
Chalcedony	— SiO_2	Native silver(?)	— Ag
Hydrohematite (turgite)	— $2Fe_2O_3.H_2O$	Cassiterite II	— SnO_2

Lindgren and Abbott [45] observed a similar three-fold division of the vein mineralization for they divided the primary ores into two phases, namely "early" and "late," and the third phase they called "supergene." However, they failed to note the important structural break between the two hypogene stages. Undoubtedly, if they had mapped the veins in detail and studied the ore deposit underground, they would have noted that the pyrite-cassiterite ores in many places are separated structurally from the silver-bearing ores.

Kozlowski and Jaskolski divided the mineralization into two epochs—hypogene and supergene. They then subdivided the hypogene epoch into three parts: pneumatolytic-hydrothermal phase; hydrothermal phase, part I; and hydrothermal phase, part II. Their two divisions of the hydrothermal phases, parts I and II, correspond to the author's pyrite-cassiterite stage and silver sulphosalt stage, respectively. However, their pneumatolytic-hydrothermal phase seems unnecessary because it is not made on the basis of vein structure or ore textures, but rather seems to be based on inferred characteristics and ore genesis. The minerals listed by them in this stage include pyrite, tourmaline, sericite, cassiterite, quartz and arsenopyrite. With the exception of tourmaline, all of these are included also in their hydrothermal phase, part I. In part, the minerals of this group are products of wall-rock alteration, but the principal reason given by them for a pneumatolytic-hydrothermal phase is based on the presence of a small amount of tourmaline in the wall rocks adjacent to the veins and in the ore.

Although the timing of wall-rock alteration with respect to vein mineralization is difficult to appraise, it is likely that in part it precedes vein mineralization and in part is contemporaneous with it. In any event, it is an important part of the hypogene mineralizing process and should be recognized as a separate phase of it. However, for purposes of description, most authors consider wall-rock alteration as a separate topic, and that practice has been followed in this paper.

Quartz-Pyrite-Cassiterite Stage.—The first veins to form in the Oruro district were made up of a massive, granular intergrowth of quartz, pyrite, and cassiterite with a small amount of arsenopyrite and possibly tourmaline present locally. It is a heavy sulphide ore with prevailing pyrite and a scant quartz

[45] Lindgren, W. and Abbott, A. C., op. cit., p. 470.

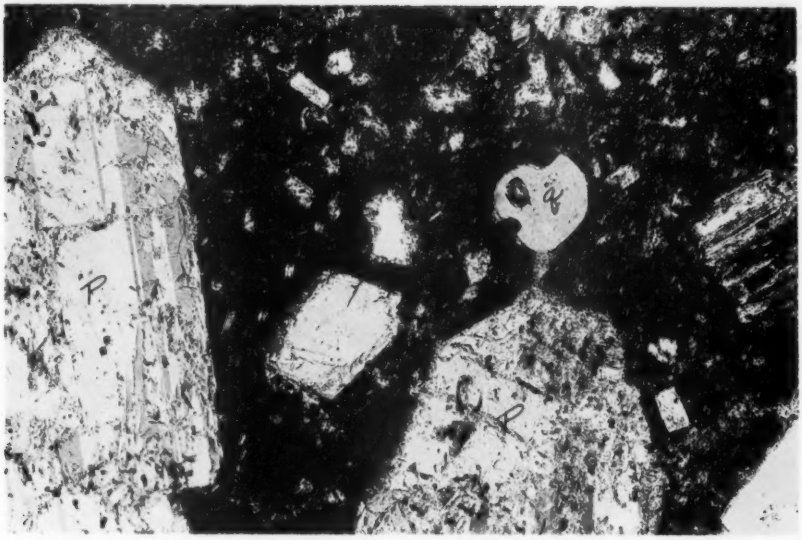


FIG. 35. Feeble phase of rock alteration of quartz latite porphyry with plagioclase phenocrysts (P), altered to sericite; biotite to chlorite; and groundmass to chlorite and kaolin. Kaolin is probably due to surface oxidation. Thin section, X Nicols, X 48.

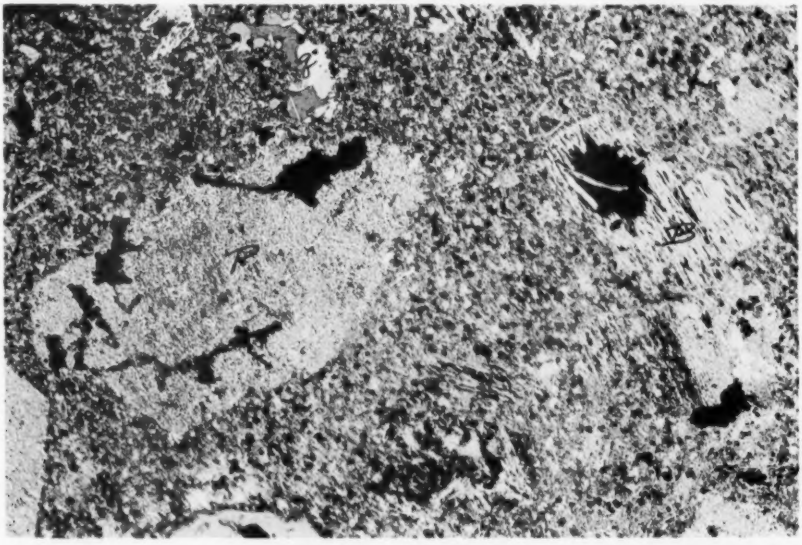


FIG. 36. Moderate phase of alteration of quartz latite porphyry with plagioclase (P) altered to sericite preserving outlines of crystals. Biotite (B) is altered to chlorite and sericite. Minor secondary quartz (q) is present. Thin section, X Nicols, X 30.

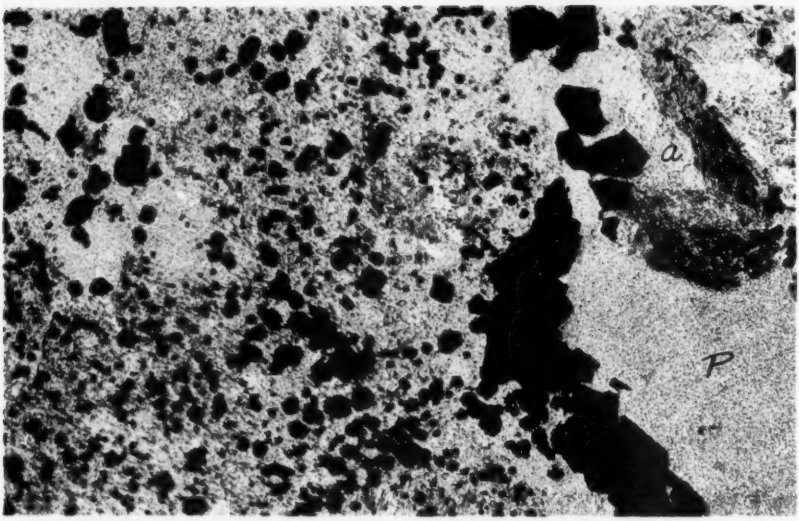


FIG. 37. Intense phase of alteration of quartz latite porphyry. Plagioclase (P) is altered to sericite. Disseminated pyrite crystals (black) replace plagioclase phenocrysts and groundmass; a few blades of alunite (A) are present. Groundmass has altered to sericite and dickite. Thin section, X Nicols, X 33.

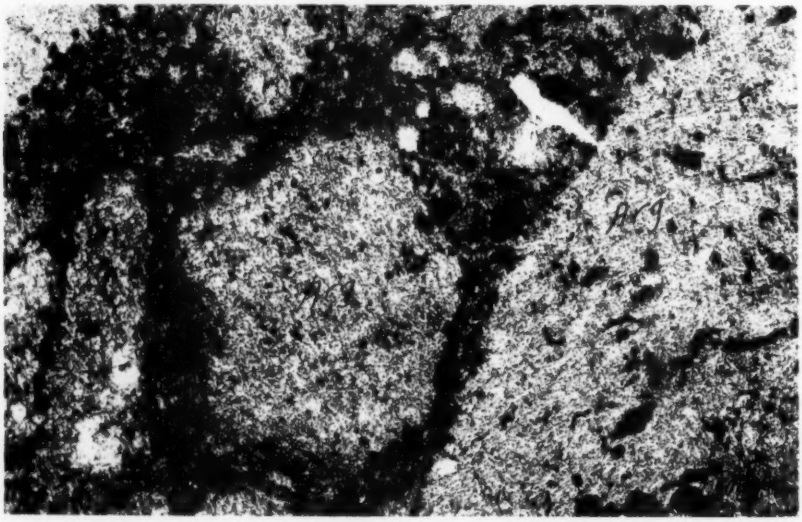


FIG. 38. San José breccia showing alteration; same as Fig. 21 with higher magnification. Porphyry fragments are an aggregate of tiny sericite flakes; matrix (black) is fine-grained sericite. Dark color is probably carbonaceous material derived from the disintegrated argillite. Thin section, X Nicols, X 130.

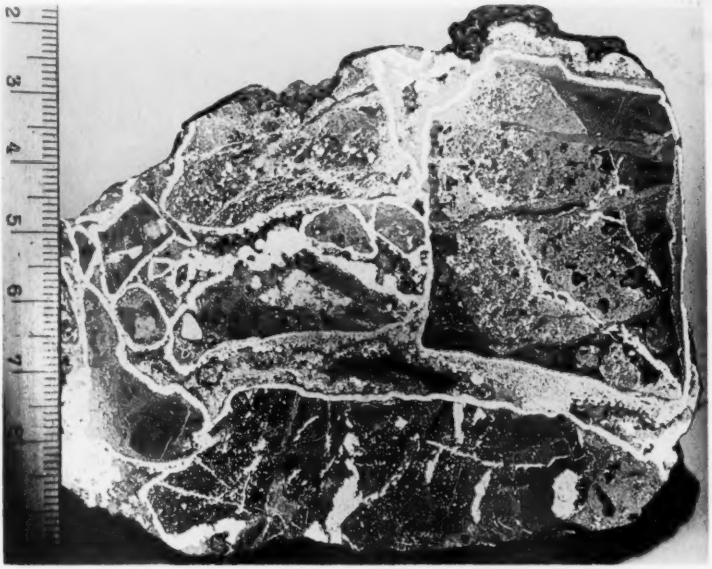


FIG. 39. Cockade Texture. Fragments of altered argillite (dark gray) surrounded and coated by pyrite (light gray); cracks and interstices filled with galena and franckeite (light gray). San José vein,—100 level stope, San José mine. Divisions on scale are 1 mm. apart. Polished handspecimen.

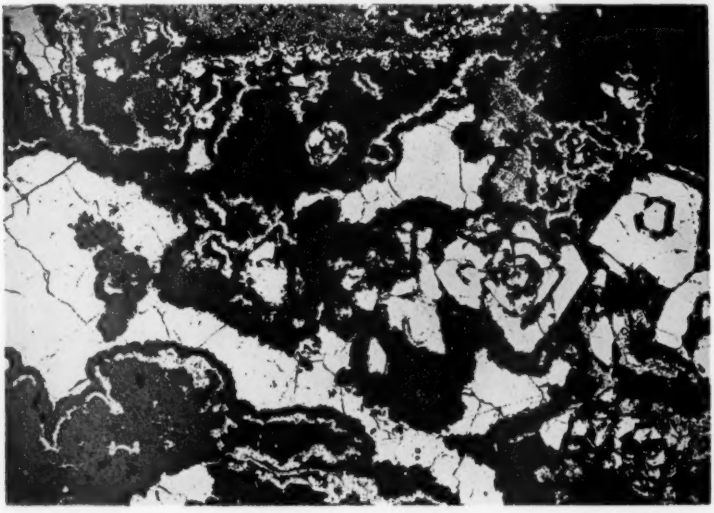


FIG. 40. Replacement textures in pyrite-cassiterite ore. Pyrite (light gray) is corroded and replaced by later cassiterite (dark gray). Nueva vein, 130 level stope, San José mine. Polished section, X 35.

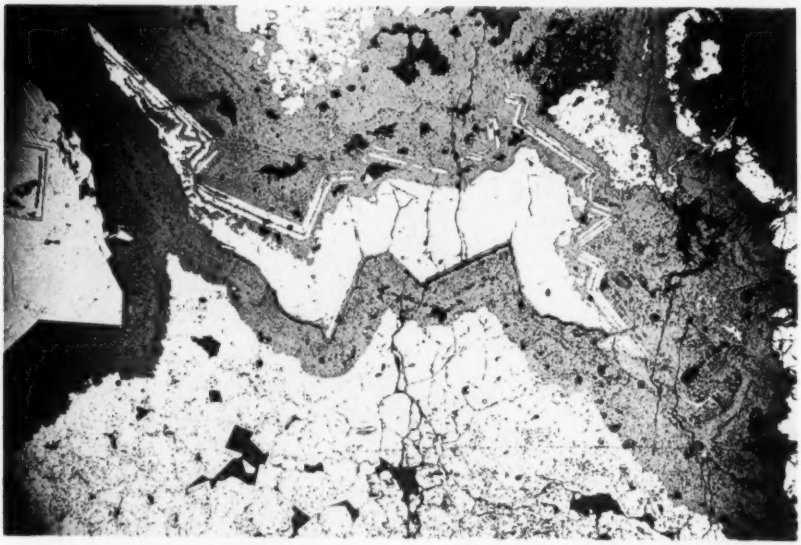


FIG. 41. Replacement textures in pyrite-cassiterite ore. Pyrite (light gray) partially replaced by cassiterite (dark gray). Residual bands of pyrite form a zoning texture. Nueva vein,—100 level, San José mine. Polished section, X 20.

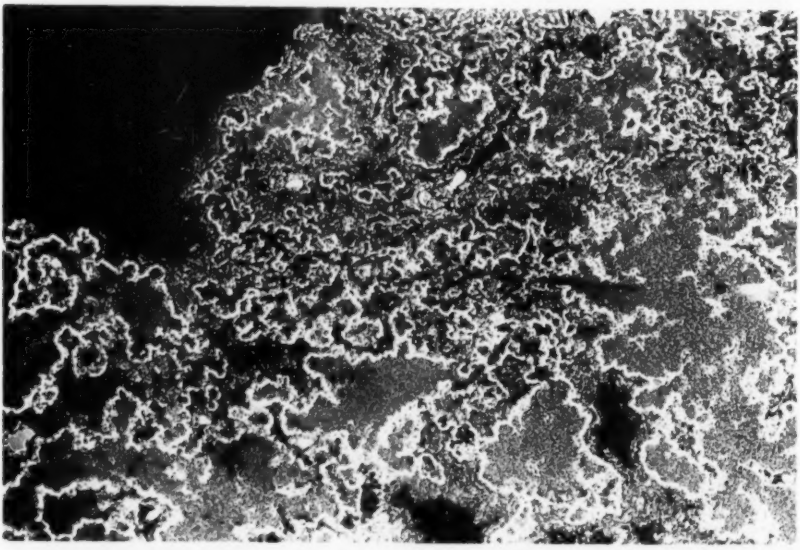


FIG. 42. Two types of cassiterite. The fine-grained variety, type "a" is stippled gray; the coarser variety, type "b", surrounds the first in lacy bands of white. Bronce vein, San José mine. Thin section, X 30.

LIBRARY OCT 12 1948

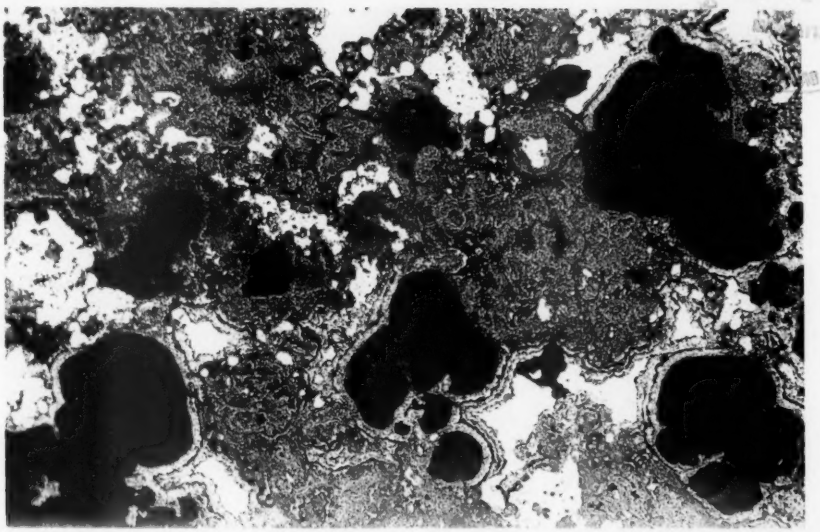


FIG. 43. Rounded grains of pyrite (black) coated by concentric growths of cassiterite (dark gray). Later quartz (white) filled in around cassiterite. The concentric texture of the cassiterite is sometimes referred to as "colloform" texture. Nueva vein, San José mine. Thin section, X 42.

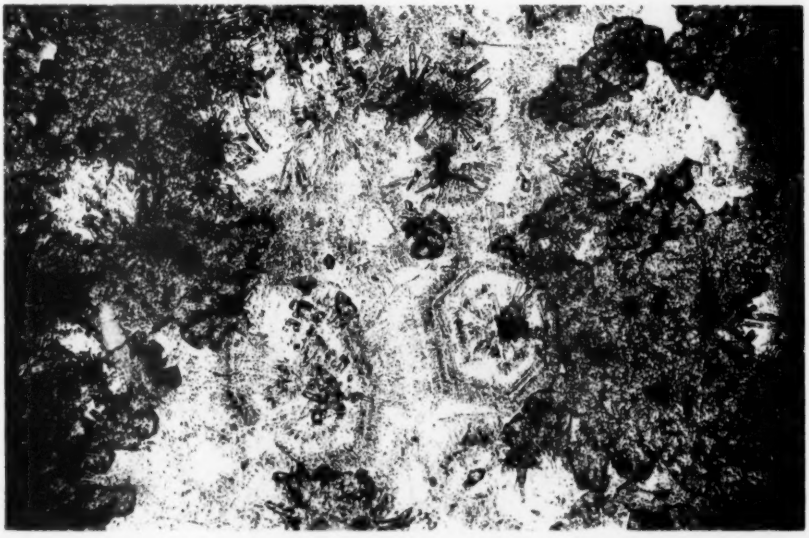


FIG. 44. Shows two varieties of cassiterite: coarse-grained aggregates, type "b", and acicular needles, type "c". Note that needles cluster around and radiate from type "b" (dark gray). Quartz (white) fills in around the cassiterite. Small inclusions in the quartz form hexagonal and elliptical outlines. Crossed nicols show the former are inclosed in three quartz grains of different optical orientation, which together give a wavy extinction. Grande vein, —116 level, La Colorada mine. Thin section, X 80.

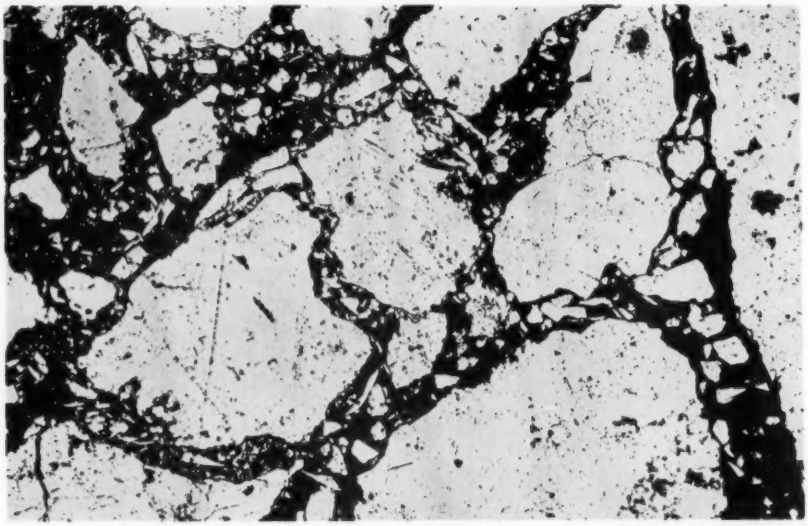


FIG. 46. Cassiterite-pyrite ore showing breccia texture. Pyrite (light gray) partly shattered and cut by veins of cassiterite and quartz (black). Small subangular fragments of pyrite ore occur in the cassiterite, indicating earlier pyrite. Grande vein, —116 level, La Colorada mine. Polished section, X 16.

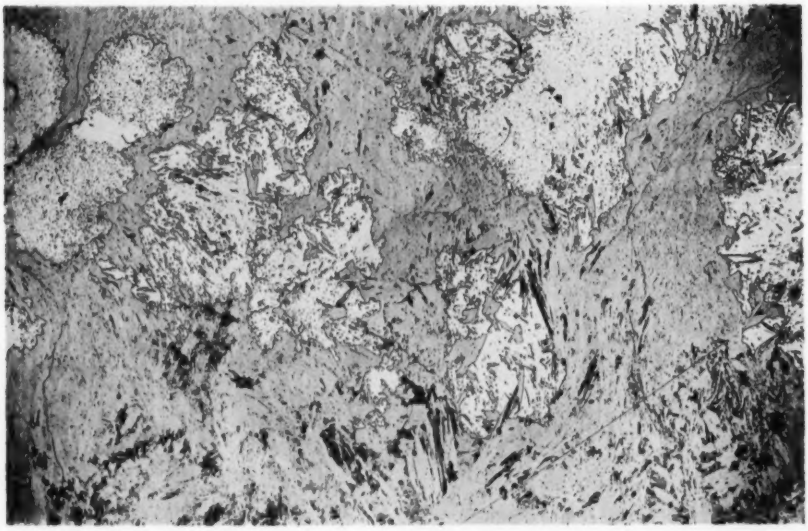


FIG. 48. Silver ore with residual grains of pyrite (light gray) in zinkenite (medium dark gray). The characteristic bladed texture of the zinkenite is seen on close examination. Purísima vein, Second level, Socavón mine. Polished section, X 38.

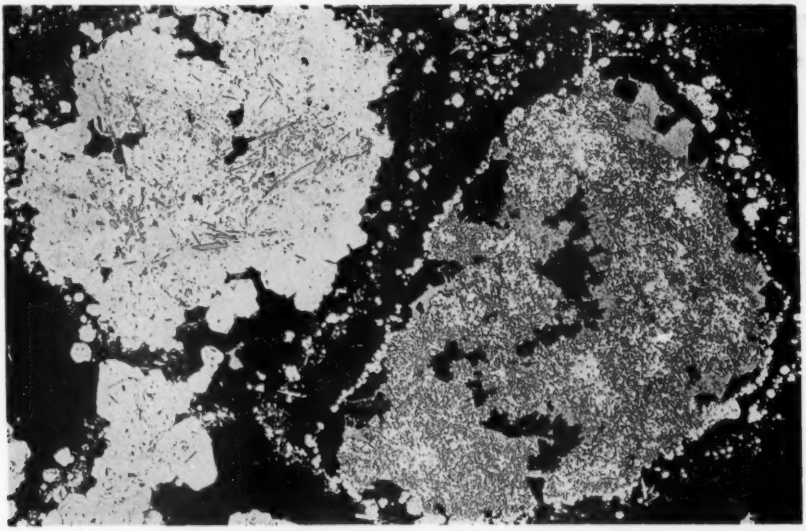


FIG. 49. Pyrite and zinkenite ore showing selective replacement. Pyrite (light gray) replaced by blebs and plates of zinkenite (dark gray). Pyrite was earlier partly replaced by cassiterite (black), giving embayments in pyrite and an "island and sea" texture of residuals of pyrite in cassiterite. Purísima vein, Socavón mine. Polished section, X 37.

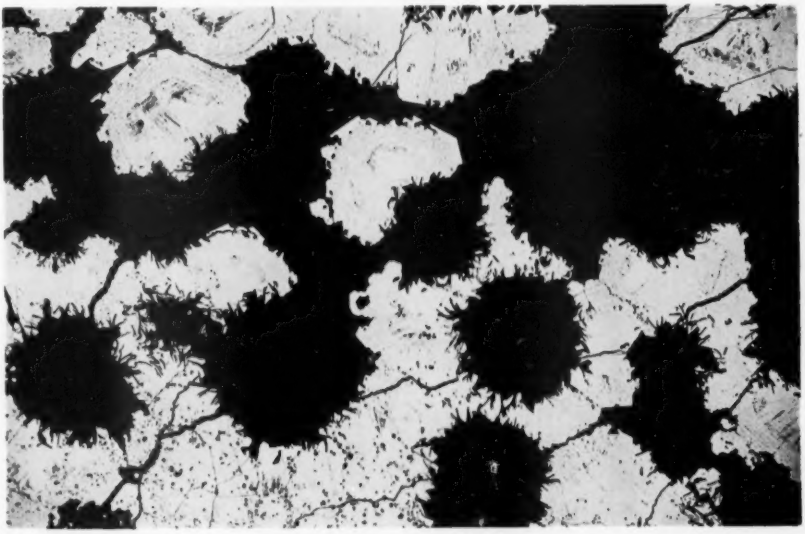


FIG. 50. "Cogwheel" texture developed by replacement of pyrite (light gray) by sphalerite (dark gray) is shown. The origin of the spines around the circular areas of sphalerite is unknown. Grande vein, La Colorada mine. Polished section, X 40.

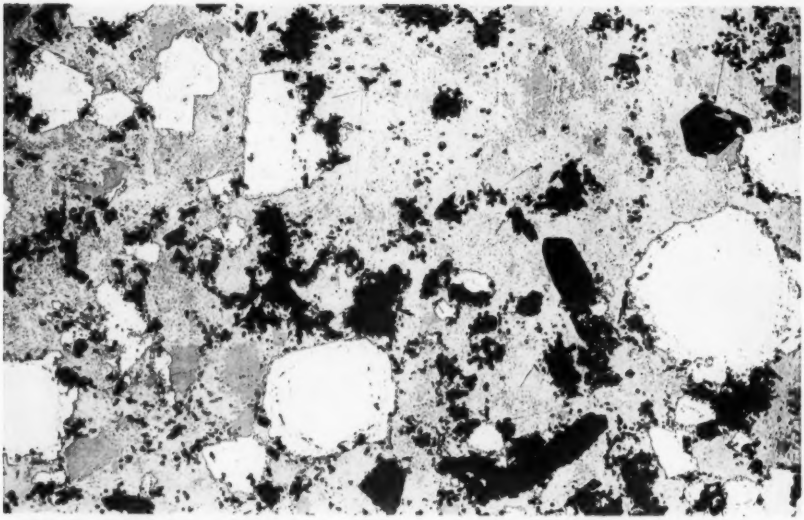


FIG. 51. Residual grains of pyrite (white), quartz (black), cassiterite (black), and stannite (medium-dark gray) in a field of gray zinkenite. Grande vein, —146 level, La Colorada mine. Polished section, X 40.

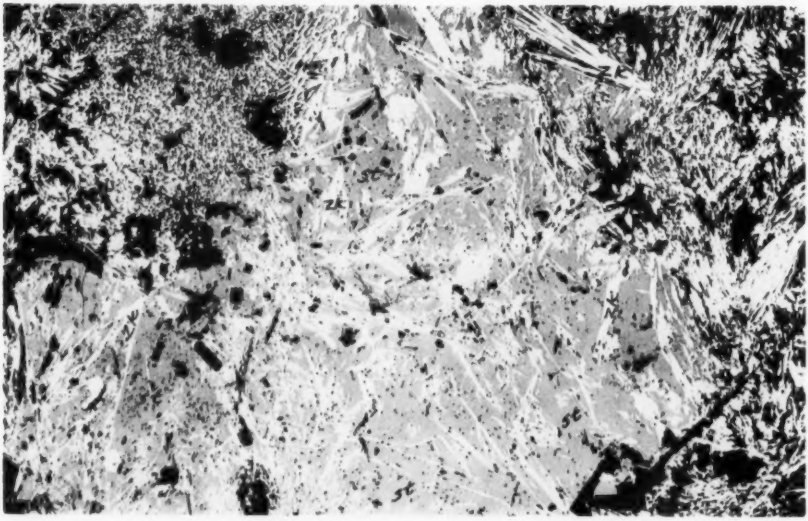


FIG. 52. Residual grains of stannite (st), (medium gray) with plates of zinkenite (zk) are shown. Bronce vein,—200 level, San José mine. Polished section, X 70.

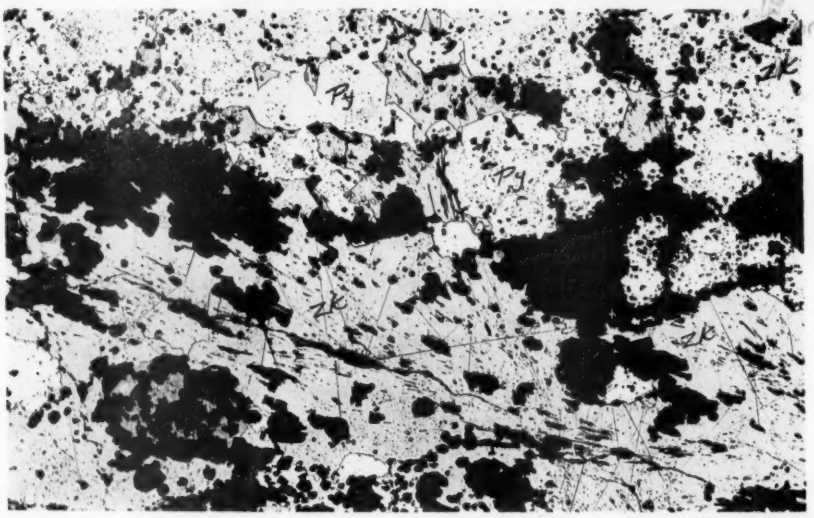


FIG. 53. Replacement textures with pyrite (py) and cassiterite (black) replaced by zinkenite (zk). Subangular, residual fragments of pyrite and cassiterite occur in zinkenite. Nueva vein,—150 level, San José mine. Polished section, X 45.

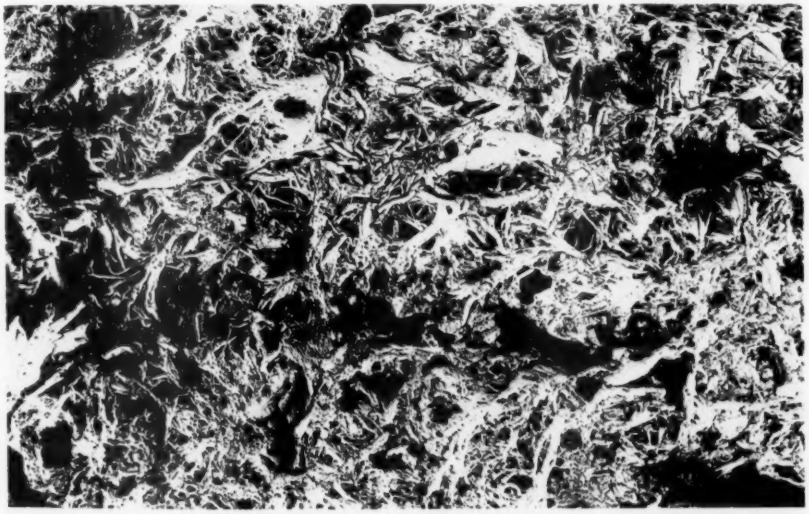


FIG. 54. Franckeite in bladed texture. Note characteristic curving habit of blades. Dark background is gangue. Grande vein, —206 level, La Colorada mine. Polished section, X 17.

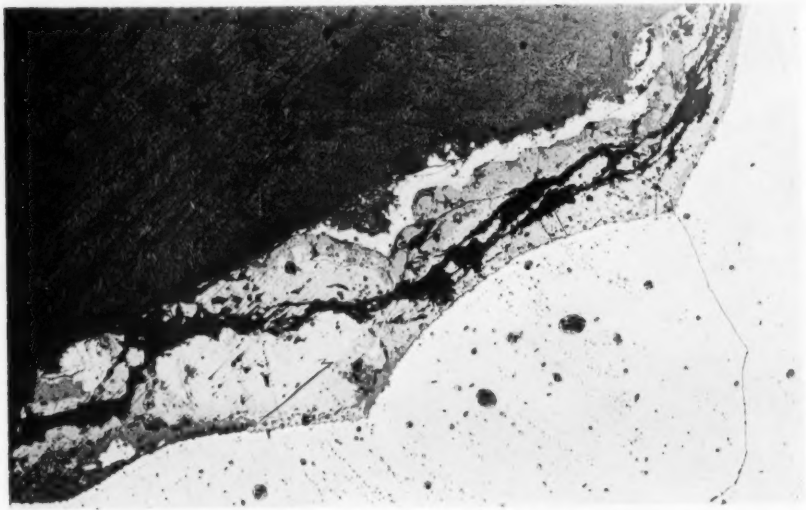


FIG. 55. Banded texture. Marcasite (white) with scalloped border coated by hematite and an unknown mineral. Crucero vein, 75 level, San José mine. Polished section, X 30.

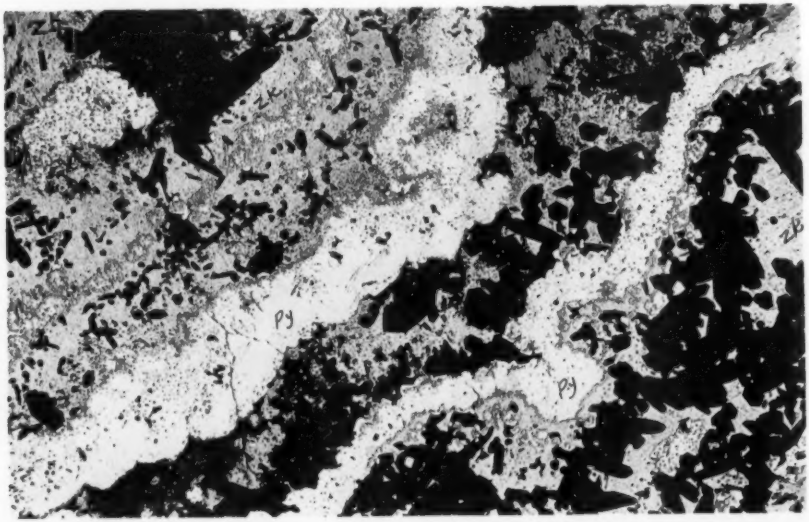


FIG. 56. Banded texture in pyrite (py) and zinkenite (zk). Black grains are quartz where euhedral and cassiterite where irregular. Unnamed vein between San Juan and San José veins.—100 level, San José mine. Polished section, X 16.

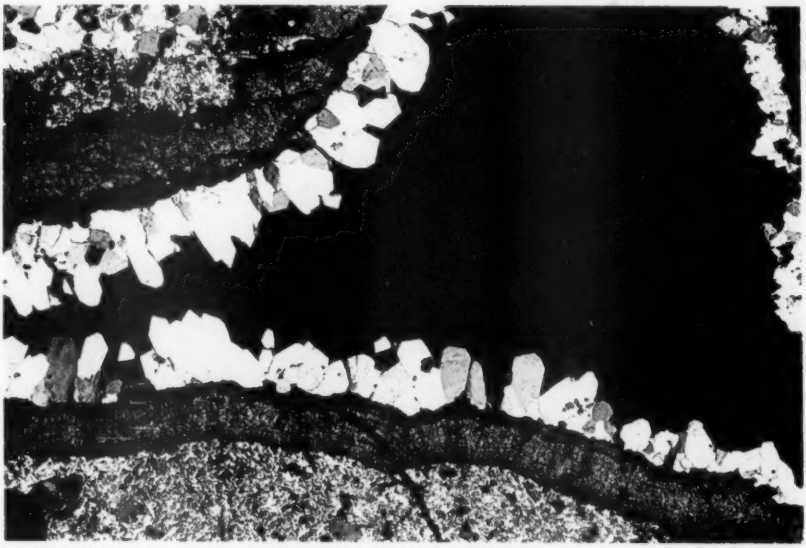


FIG. 57. Characteristic pacos tin ore; banded cassiterite (gray) coating altered wall rock (porphyry). Quartz (white) in euhedral crystals coat cassiterite in a druse texture. Limonite and jarosite (black) fill the residual cavity. From west slope of Todos Santos hill. Thin section, X 21, polaroid.

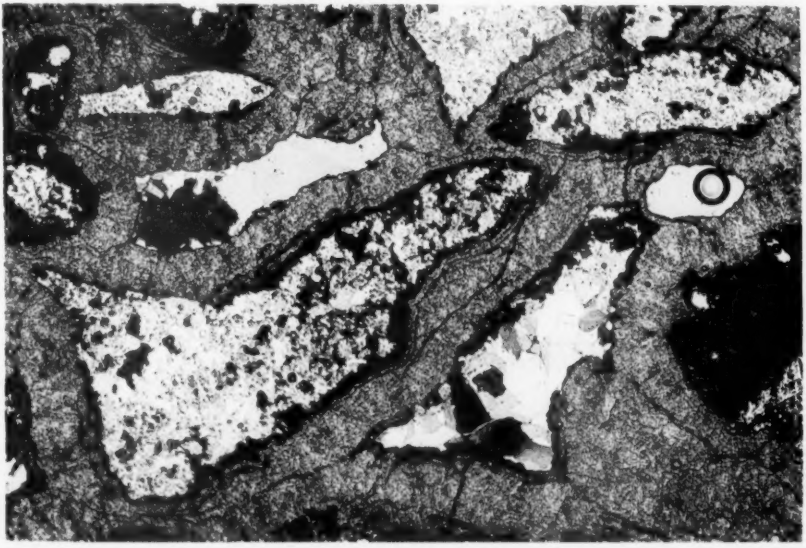


FIG. 58. Pacos tin ore. Cassiterite (gray, stippled) in typical boxwork texture. Later quartz (white and light gray) in an interlocking, granular texture fills in around the cassiterite. From the west slope of Todos Santos hill. Thin section, X 30, polaroid.

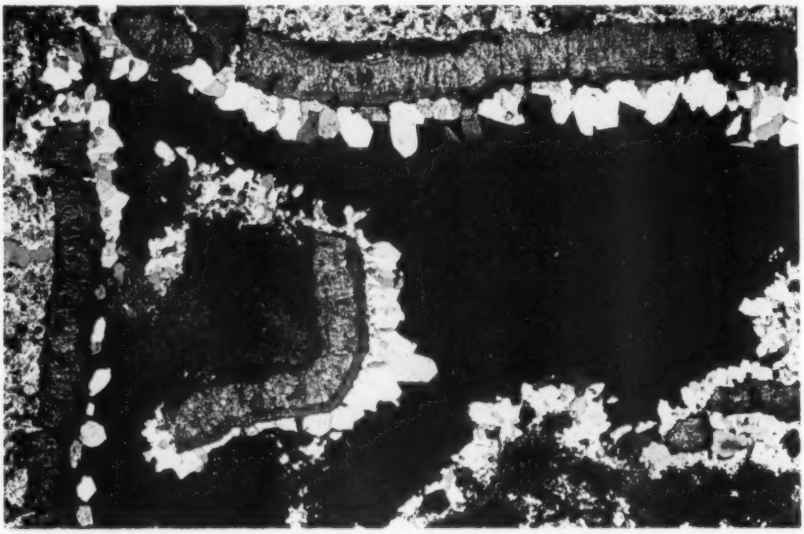


FIG. 59. Typical pacos tin ore. A cassiterite band (stippled, gray) coats altered wall rock with a druse texture of euhedral quartz (white) coating cassiterite. Jarosite (black) fills the space between the bands. A fragment of cassiterite probably broken from the main band is in left center. West slope of Todos Santos Hill. Thin section, X 20, polaroid.

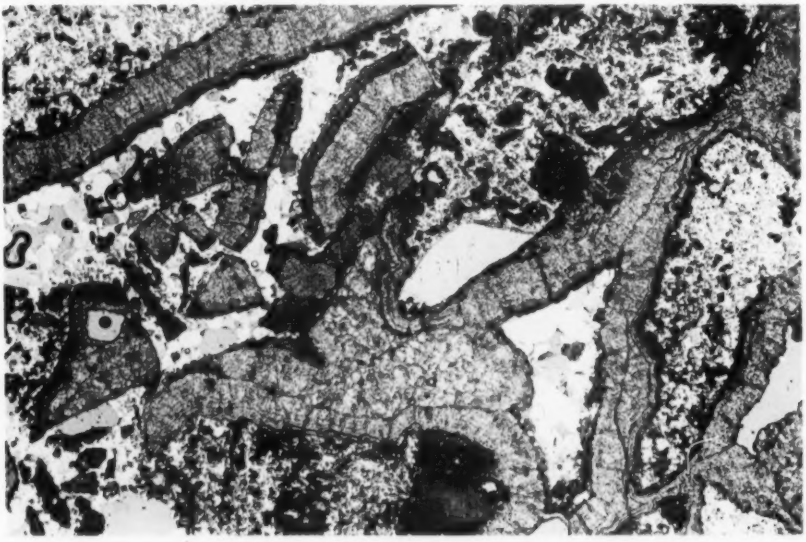


FIG. 60. Typical boxwork texture of cassiterite in pacos ore. Quartz fills in around the cassiterite bands and fragments. Brecciated fragments of cassiterite bands are on left side. Thin section, X 22, polaroid.

gangue. Cassiterite is generally inconspicuous and is not visible, unless the ore contains over 2.5 to 3 percent tin.

The ore is extremely porous and vuggy with innumerable druse-lined cavities which vary in size from less than a millimeter to about one meter. The larger cavities are usually elongated parallel to the strike of the veins. Crude banding is common in the ore; this may be due in part to crustification, but in a large measure probably developed from replacement of sheeted wall rock. Thin slabs of altered and partly replaced porphyry, argillite, and San José breccia enclosed in the veins parallel to their walls suggest this origin. Where San José breccia forms the walls of a vein, "cockade" texture has developed with pyrite coating resistant fragments of argillite and porphyry (Fig. 39).

Pyrite.—Pyrite is the most abundant vein mineral in the Oruro district and usually makes up over 85 percent of the ore. It forms massive aggregates with an interlocking granular texture; in many places, it has a mosaic texture with the grains outlined by crystal boundaries; and is also found as well-formed crystals lining the many vugs in the ore. Octahedrons are the most common crystal form, but cubes, pyritohedrons, and complex forms are found frequently. The crystals are seldom over 2 mm along the greatest dimension and range in size down to those individuals distinguished only under the microscope. Figures 40 to 46, photomicrographs of the quartz-pyrite-cassiterite ore, illustrate the characteristics of this stage.

Cassiterite.—Where cassiterite is clearly discernible, it has a light, gray-brown to tan color with a dull stony lustre. In places, it is almost colorless; and in fact Oruro cassiterite is one of the lightest colored in Bolivia. It is difficult for one unfamiliar with the ore to recognize the tin-bearing mineral without a series of tests, but after some experience it is readily identified. Because of its high specific gravity (6.8 – 7.1), the cassiterite imparts a distinct "heftiness" to the ore which serves to distinguish the ore from waste.

Under the microscope, cassiterite appears in a variety of forms and aggregates. Fine-grained massive aggregates form most of the high-grade ore, but "needle tin" and a very fine-grained, banded variety are common, particularly in the pacos ore. In general, four types of cassiterite may be distinguished, but all gradations between them are found.

(a) A very fine-grained aggregate of crystals with an interlocking granular texture, light gray-brown in color, which appears amorphous in thin sections of abnormal thickness, but proves to be definitely crystalline in sections of normal thickness and under high magnification (Fig. 42).

(b) A coarse-grained variety found as disseminated crystals, as aggregates with an interlocking granular texture, and as coatings or concentric growths surrounding the fine-grained variety or rounded grains of pyrite (Figs. 42–45). In places where individual grains are found, the cassiterite has a prismatic or rhombic shape.

(c) An acicular variety made up of slender prismatic crystals radiating from a coarse-grained patch of cassiterite or as disseminated crystals. When this "needle tin" is truncated at right angles to the direction of elongation by the cut of the thin section, the grains with crystal outlines of type "b" are formed. It is this variety of "needle tin" that Kozlowski and Jaskolski possibly misidentified as tourmaline (Fig. 44).

(d) A distinctly banded type found in the primary ore but more abundantly in the pacos ore which forms coating texture and box-work texture (Figs. 43, 57, 58, 59). This variety where developed in reniform and botryoidal shapes may be the "wood-tin" reported as found in the district by Kozlowski.

Cassiterite is found in well-defined veins and oreshoots, but in general its distribution within the veins is rather irregular. The usual occurrence is in small masses, pockets, filling of fissures, and as very fine disseminations in pyrite. Many areas of nearly barren pyrite indicate that cassiterite deposition was not nearly as extensive as that of quartz and pyrite, and that there is a decided tendency of the cassiterite to occur in shoots. Large masses were left on the upper mine levels by the early miners who were interested only in silver; but these have been nearly mined out now. Similar pockets have been found on the lower mine levels, but in general they are fewer in number, smaller in size, and lower in grade.

Quartz.—Quartz is the only important gangue mineral in the first stage of the vein mineralization. It is fairly uniformly distributed through the ore and makes up between 5 and 15 percent of the total volume. Quartz is inconspicuous in the hand specimen of the pyritic ore, but under the microscope its abundance is at once apparent. It forms granular aggregates filling pores in rocks and locally makes well defined veinlets. Euhedral crystals with flamboyant texture are sometimes found where the quartz is coarse-grained. In places quartz has a wavy extinction possibly due to deformation but more likely to recrystallization.

Summary.—The sequence of events of the first stage of mineralization may be determined in part in the hand specimens, but the final answer is obtained by the use of the microscope (Fig. 47). A study of the textures indicates that mineral deposition occurred in overlapping and successive stages. Probably quartz was the first mineral to form, because it is found in the wall rocks adjacent to the veins replacing the rock-forming minerals. However, it is likely that much of the silicification of the wall rock accompanied the deposition of quartz of a later stage which fills open spaces left after pyrite was deposited. Figure 43 shows quartz with an interlocking, granular texture filling in and around banded cassiterite and pyrite.

Conclusive evidence is present that pyrite deposition both preceded and followed the formation of cassiterite. Probably the pyrite was in part contemporaneous with the cassiterite when an entire vein is considered. Figures 40 and 41 show early pyrite partially replaced by cassiterite. Residual inclusions of pyrite ore are found in the tin mineral; cassiterite veins cut through the pyrite; and replacement has resulted in residual zonal bands of the pyrite found in many sections (Fig. 41). In places, early pyrite in round grains is coated by cassiterite, giving a colloform texture (Fig. 43). Pyrite later than cassiterite is found in veins cutting across the concentric cassiterite of type "b", as illustrated in Figure 42, and in druses lining the cavities of cassiterite ore.

The deposition of cassiterite began after much pyrite had formed, and ceased while pyrite and quartz continued to precipitate. The series of illustrations cited above shows that in part cassiterite replaces pyrite and in

part has been veined by pyrite. Later quartz fills in around cassiterite which forms concentric growths about pyrite. The pyrite forming druse-lined vugs seen in the hand specimens is later than cassiterite. Kozlowski and Jaskolski

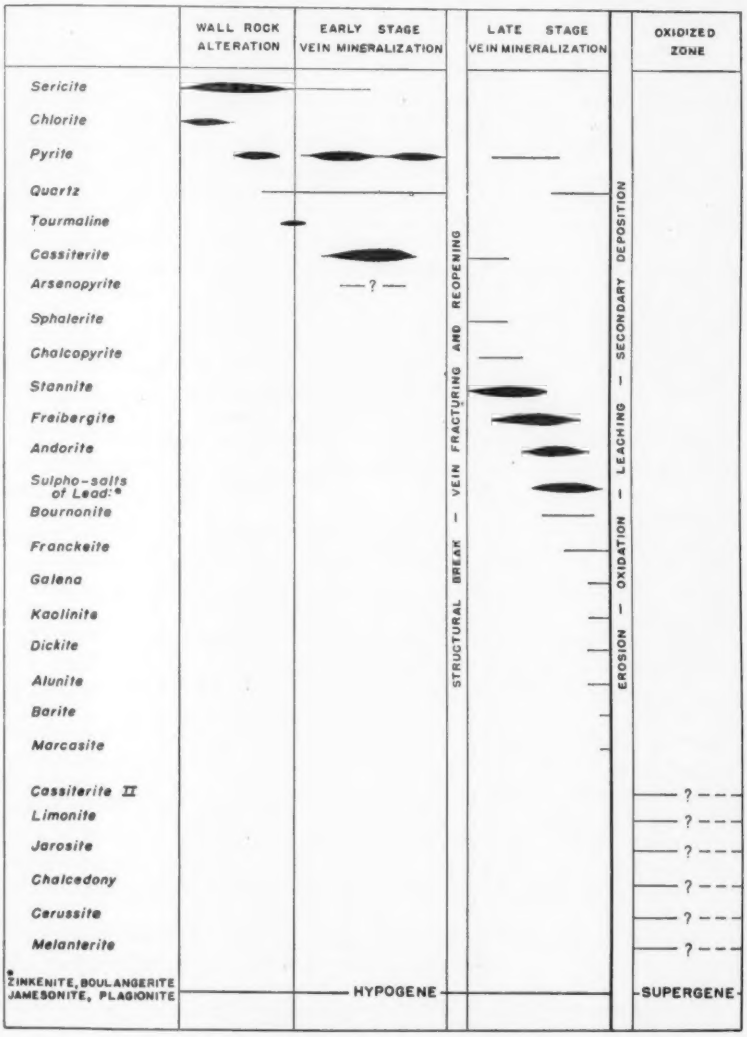


FIG. 47. Graphic representation of mineral sequence, Oruro, Bolivia.

observed that cassiterite crystals are sometimes found in vugs attached to late sulphosalts, as well as in the reverse relations. This indicates that there was some late cassiterite, but the amount was so small as to be relatively insignificant. This late deposition may in fact have been supergene. The mineral sequence is illustrated graphically in Figure 47.

Silver Sulphosalt Stage.—The minerals of the silver sulphosalt stage form far more complex ores than those of the pyrite-cassiterite stage, and are chiefly sulphosalts and sulphostannates which carry silver, lead, tin, antimony, and copper. The most abundant minerals are tetrahedrite (variety freibergite), andorite, boulangerite, bournonite, zinkenite, jamesonite, galena, stannite, and franckeite. Traces of sphalerite, pyrite, and chalcopyrite are found locally. As far as is known, the other primary minerals listed at the beginning of the chapter are present in small amounts only.

Andorite and freibergite are the chief source of silver in the Oruro veins. Some silver is obtained from zinkenite and bournonite, but it is not known what relative proportion of the production comes from these minerals. With the exception of andorite ($2PbS, Ag_2S, 3Sb_2S_3$), silver does not appear in the formula of any of the minerals mentioned above, but its presence in many of them, including tetrahedrite, zinkenite, bournonite, and galena, has been verified [46] by an assay test of individual crystals and by microchemical tests in the laboratory at Harvard University. The potassium mercuric thiocyanate test [47] usually reveals a trace of silver in these minerals. The ammonium bichromate test was less successful, and this result conforms to the experience of Short,[48] who concluded that this test could not be applied to freibergite with consistent results.

The ores of the sulphosalt stage are found in a variety of textures including coating, banding, and replacement types. Partially filled vugs are common with druse linings and fibrous growths. Compact, granular masses of galena, franckeite, and lead sulphosalts are equally common.

Under the microscope, replacement textures are found, and residual inclusions of quartz, pyrite, and cassiterite are common in the sulphosalt minerals, although in many places it is apparent that later minerals have filled in around the minerals of the cassiterite stage and replacement has been negligible. Within the sulphosalt stage, replacement has occurred during deposition and tends to be remarkably selective. Pyrite and stannite are commonly hosts for zinkenite, whereas the surrounding minerals, generally quartz and cassiterite, are not replaced. Stannite is found almost wholly in residual grains and in most cases has been replaced by zinkenite only. Pyrite was particularly susceptible to attack by zinkenite. Scattered plates and fibers of zinkenite are found within the heart of rounded grains and suggest selective replacement (Figs. 48, 49).

Although replacement textures are common in the sulphosalt stage, most of the minerals were deposited in open spaces and filled vugs, residual cavities,

[46] Personal communication of Mr. Dirk van Gemern, Mine Manager.

[47] Short, M. N., Microscopic determination of the ore minerals: U. S. Geol. Survey Bull. 825, p. 148, 1931.

[48] Short, M. N., op. cit., p. 149.

and pores in the cassiterite ore. Independent veins of galena and sulphosalts of this stage appear to have formed principally by filling open fractures which followed and cut across the older cassiterite veins.

Sphalerite is found in a few localities but is not abundant. A few scattered areas were noted in the polished sections of the ores of the second stage. It replaces quartz, pyrite, and cassiterite, and in turn is replaced by chalcopyrite, stannite, and all the sulphosalts. An interesting texture was found in one specimen where sphalerite has replaced pyrite, resulting in a texture resembling "cogwheels" (Figs. 50, 51). Rounded areas of sphalerite have formed in the pyrite, and around the margins between the two minerals small spines of sphalerite extend into the pyrite.

Chalcopyrite, like sphalerite, is found in only a few localities and nowhere is abundant. Under the microscope, a few small grains were found in several polished sections. It appears to have replaced sphalerite, and in turn is replaced by stannite and the sulphosalts. It occurs most commonly as residual inclusions in tetrahedrite and zinkenite.

Stannite (Cu_2S, FeS, SnS_2) is a common mineral in the ores of the second stage and is found in nearly all of the veins in small amounts. Except in a few places, such as the Verde vein, 280 level, San José mine, which is nearly pure stannite with a maximum width of about 20 cm, stannite is not readily detected, because it is mistaken for pyrite which it resembles in color and lustre. Where isolated, stannite has a bright, metallic lustre with a decided greenish cast. It is usually massive, granular in texture, rarely euhedral, and has a hardness of about 3.5.

Under the microscope, stannite proves to be very abundant. In fact, it was found in small amounts in nearly all the polished sections of the second-stage minerals.

Stannite forms a massive, granular texture and is usually found in residual grains. In places, residual inclusions of cassiterite, pyrite, and quartz are found in it. The stannite has been replaced by all of the sulphosalts, but in the greater number of cases zinkenite is the attacking mineral. Residual grains of stannite were found replaced by franckeite in specimens from the lower levels of the Grande vein.

The place assigned to stannite in the mineral sequence is different from that given by Kozlowski.[49] He found stannite covering crystal faces of freibergite and andorite in vugs. Therefore, some of the stannite was precipitated after these minerals. However, the bulk of the stannite, as indicated by the relations found in many polished sections, was deposited before the formation of andorite and freibergite.

Andorite and tetrahedrite are the chief sources of silver in the Oruro veins. Several references to these minerals are found in the literature where their crystallography and physical properties are described.[50] Tetrahedrite is always the silver-bearing variety called freibergite. It is found in massive, granular replacement products of the earlier minerals, in well-defined veinlets, and commonly in small tetrahedrons up to 10 mm across. Andorite is com-

[49] Kozlowski, R. and Jaskolski, S., op. cit., p. 45.
[50] Spencer, L. J., op. cit. (three references).

mon in small, striated, orthorhombic crystals with a brilliant, black, metallic lustre. Unusual crystals up to 20 mm long are found occasionally, according to Kozlowski.[51] Andorite is abundant in the Itos mine and is sometimes found in the San José and Socavón mines.

Freibergite is most abundant in the San José and La Colorada mines, but, like andorite, also is found elsewhere. It is the principal silver-bearing mineral of the Grande vein in the ore shoot extending from the -116 level to the -176 level. According to Lindgren, andorite is later in age than tetrahedrite. This age relation is indicated in the author's specimens, although andorite and freibergite are found together in only a few sections. Both andorite and tetrahedrite were replaced by zinkenite.

Lead Sulphosalts.—Sulphosalts of lead are found in abundance in practically all of the Oruro veins and are particularly prominent in those parts of the veins that have a high silver content. They form a complex group of minerals with similar texture and paragenesis, and include zinkenite, boulangerite, jamesonite, plagionite, and bournonite. Semseyite, meneghinite, stephanite, freieslebenite and owyheeite have been reported from Oruro and probably occur in small amounts. Keeleyite and plumosite have also been reported from Oruro, but these are not now recognized mineral species. Keeleyite, first described by Gordon [52] in 1922 as a new lead-antimony sulphosalt ($Pb_2Sb_6S_{11}$) from Oruro, has been shown by Vaux and Bannister [53] on the basis of X-ray analysis to be identical with zinkenite. Plumosite is not now regarded as the name of an individual mineral, but as a descriptive term which may be applied to jamesonite, boulangerite, zinkenite, or any other lead sulphosalt that has a plumose texture or that occurs in a fibrous aggregate.

The lead-antimony sulphosalts formed in part by replacement of cassiterite, pyrite, stannite, and other minerals, but more commonly they occur as vein fillings, coatings and druses along independent fractures and in vugs. Massive ore is plentiful and in places is made up of radiating prismatic and bladed crystal growths of boulangerite, zinkenite, or jamesonite, or mixtures of these minerals. "Feather ores" or "federerz" are common. Tiny acicular crystals, a few millimeters long, are very abundant. These are found in individual hairlike needles in vugs in the pyritic ore and as felted masses coating earlier minerals.

In their general appearance, especially where the plumose texture is best developed, the sulphosalts suggest a supergene origin, but their structural position in the deeper veins and theoretical considerations of the behavior of antimony and lead during oxidation and supergene processes preclude the possibility of this origin.

The individual minerals of the lead sulphosalt group are very difficult to distinguish by ordinary laboratory methods. Impurities and mixtures confuse the identification by chemical methods, and the reaction of the minerals to etch reagents on polished surfaces is not always conclusive and does not

[51] Kozlowski, R. and Jaskolski, S., op. cit.

[52] Gordon, S. G., Acad. Sci. Philadelphia, Proc. 74, p. 101, 1922.

[53] Vaux, G. and Bannister, F. A., The identity of zinckenite and keeleyite: Mineral. Mag., vol. 25, p. 221, 1938.

serve to distinguish members of the group. Chemical analyses or X-ray methods are usually necessary for final determination of individual specimens. Under the reflecting microscope the minerals appear light gray to galena white, are soft, usually have weak pleochroism and are distinctly anisotropic. They effervesce with 1 : 1 HNO_3; give a positive reaction with 1 : 1 HCl, although in some cases only the fumes tarnish; are negative with KCN, $FeCl_3$ and $HgCl_2$. Most members of the group give a strong reaction with KOH, but boulangerite and meneghenite, according to Short,[54] are negative. However, etch tests of several boulangerite specimens gave iridscent stains that rubbed off. As the KOH test for zinkenite sometimes behaves in a similar way, it cannot be considered diagnostic for all specimens. To confirm his identifications, the author had several X-ray analyses made in the chemical laboratories of the United States Geological Survey.[55]

Zinkenite ($Pb_6Sb_{14}S_{27}$) is common in almost all the silver-bearing veins of Oruro and occurs in massive veins as well as in columnar to radial fibrous aggregates and in felted masses of tiny acicular crystals coating vugs and earlier pyritic ore. Zinkenite replaces pyrite and stannite selectively in many places (Figs. 48–51) and residual grains of these minerals in zinkenite and other sulphosalts are very numerous. Blades of zinkenite are found replacing stannite in many places (Figs. 51, 52).

Zinkenite from the Itos mine was first described by Stelzner.[56] Here it is associated with andorite. Lindgren and Abbott,[57] and somewhat later Kozlowski and Jaskolski,[58] confirmed the presence of zinkenite in the Oruro veins and considered it to be the common lead sulphosalt of the district. However, much of the material believed to be zinkenite is probably boulangerite. Because of the difficulty of distinguishing zinkenite from the other sulphosalts, X-ray powder photographs were made to confirm the mineral identification. Two specific-gravity measurements gave 5.125 and 5.091. These are somewhat lower than the calculated value for zinkenite, which, according to the new Dana edition,[59] is 5.22.

The Oruro zinkenite contains a small amount of silver. This has been confirmed by microchemical tests. An analysis of zinkenite by Mann published by Stelzner gave 22.54% S, 40.72% Sb, 33.04% Pb, 0.57% Ag, and 3.47% Fe. Another analysis by Helen Vassar made for Lindgren and Abbott[60] gave 34.33% Pb and 1.34% Ag. This latter specimen was composed of "finely felted feather ore" from the lower levels of the Itos mine. Although the lead and antimony content of the mineral analyzed by Mann agrees fairly well with the analyses published in the new Dana, the iron content is much too high and corresponds more nearly with the iron content of jamesonite.

[54] Short, M. N., Microscopic determination of the ore minerals: U. S. Geol. Survey Bull. 914, p. 116, 1940.

[55] The X-ray work was performed by J. M. Axelrod, to whom the author is grateful for generous help.

[56] Stelzner, A. W., Die silber-zinnlagerstatten Bolivias: Zeitschr. d. Deutsch. Geol. Gesellschaft, vol. 49, p. 86, 1897.

[57] Lindgren, W. and Abbott, A. C., op. cit.

[58] Kozlowski, R. and Jaskolski, op. cit.

[59] Dana's System of Mineralogy, vol. 1, p. 476, 1944.

[60] Lindgren, W. and Abbott, A. C., op. cit.

Possibly this is due to impurities. Zinkenites tested chemically by the author gave positive tests for iron.

Boulangerite ($Pb_5Sb_4S_{11}$) was first noted in the Oruro ores by Lindgren and Abbott;[61] but no comment was made. Kozlowski and Jaskolski did not mention it. However, X-ray analyses of several specimens recently made (1947) indicate that boulangerite is much more common in the Oruro veins than was previously believed. Undoubtedly much of the material previously identified as zinkenite, jamesonite, or other lead sulphosalts is boulangerite. Boulangerite is similar to these minerals in its physical appearance, crystal habit, and reaction to etch tests. However, it does not have a basal cleavage and the chemical test for iron is negative; thus it can be distinguished from jamesonite.

Several bladed, prismatic crystals and a single tiny, acicular crystal tentatively identified as zinkenite were tested by X-ray powder photographs and proved to be boulangerite. Specific-gravity tests of these specimens on a Berman microbalance gave 5.65, 5.78, and 5.91. Under the reflecting microscope the boulangerite was light gray in color, soft, anisotropic, showed no cleavage and gave the following etch reactions: effervesces with HNO_3; doubtful positive with HCl; negative to KCN, $FeCl_3$, $HgCl_2$; with KOH gave a slight brown to iridescent stain that rubbed off. The chemical test for iron was negative.

Jamesonite ($Pb_4FeSb_6S_{14}$) from Oruro was first described by Spencer,[62] whose determination was based on the measurement of the prism angle (79°) and the presence of a good basal cleavage. Other specimens from the Socavón de la Virgen believed to be zinkenite were shown by Spencer, on the basis of the same chracteristics, to be jamesonite. Jamesonite, however, is not abundant in the Oruro veins, as are zinkenite and boulangerite. Lindgren and Abbott[63] stated that they did not identify the mineral in their collection. Moreover, Kozlowski and Jaskolski,[64] and later Campbell,[65] questioned the presence of jamesonite at Oruro. An exhaustive study by Berry[66] on jamesonite from Oruro and from Cornwall, however, has definitely established the fact that jamesonite occurs in the Oruro veins. His conclusions have been verified by the author on a specimen obtained from the National Museum in Washington, D. C.

Berry noted that "jamesonite is notoriously difficult to distinguish from boulangerite in ore specimens." He might have added that zinkenite and other sulphosalts are, also. Specific-gravity measurements by Berry ranged from 5.46 to 5.63, whereas the calculated value is 5.67. Under the reflecting microscope jamesonite on polished surfaces is white, strongly anisotropic and usually shows a good basal cleavage. The longitudinal cleavage is less distinct.

[61] Lindgren, W. and Abbott, A. C., op. cit.

[62] Spencer, L. J., Notes on some Bolivian minerals: Mineral. Mag., vol. 19, no. 67, pp. 308–344, 1907.

[63] Lindgren, W. and Abbott, A. C., op. cit.

[64] Kozlowski, R. and Jaskolski, S., op. cit.

[65] Campbell, Donald F., The Oruro silver-tin district, Bolivia: Econ. Geol., vol. 37, pp. 87–115, 1942.

[66] Berry, L. G., Studies of mineral sulpho-salts. II. Jamesonite from Cornwall and Bolivia: Mineral. Mag., vol. 25, pp. 597–608, 1940.

The etch reactions of jamesonite are similar to those for zinkenite and boulangerite. The KOH test is generally supposed to be diagnostic, positive for jamesonite and negative for boulangerite, but it seldom is distinctive. However, jamesonite can be distinguished from boulangerite and zinkenite by a strong microchemical test for iron and by its good basal cleavage.

According to Berry's published results, jamesonite from Cornwall (type locality) and Oruro gave identical X-ray powder photographs. Rotation and equi-inclination Weissenberg photographs on a needle crystal from the Itos mine, Oruro, gave monoclinic symmetry.

An excellent jamesonite specimen was found in the Frederick A. Canfield collection of the United States National Museum in Washington, D. C. (Museum No. C 4958), that was labelled "Santo Christo Mine, Oruro, Bolivia." This specimen is a friable mass of many tiny acicular crystals loosely aggregated in plumose and radiating groups. The crystals are dark gray to black in color, with a bright metallic lustre and are quite brittle. X-ray powder photographs of a few of the tiny crystals conformed to Berry's measurements [67] for jamesonite from the type locality in Cornwall. Moreover, the jamesonite gave a positive test for iron; and it has a fair basal cleavage. The specific-gravity measurement, 5.30, was somewhat low for typical jamesonite, but this was probably because of the porosity of the material weighed.

Bournonite ($PbCuSbS_3$) is a comparatively rare mineral at Oruro, although small amounts are sometimes found. Kozlowski and Jaskolski [68] reported that it was plentiful in the upper parts of the hypogene zone, especially in the Bronce vein, where toward the end of the last century "cogwheel" twinned crystals were found, up to 25 mm in diameter. An excellent specimen of bournonite was given the author in 1937 by D. Van Gemern, formerly Manager of Compañia Minera de Oruro. This specimen from the -146 level of the Grande vein, La Colorada mine, consists of many small, iron-black crystals perched on late quartz in small cavities in highly altered wall rock, largely replaced by pyrite and boulangerite (?). Many of the crystals are short prismatic to tabular in habit, but a few have the cogwheel aggregates due to twinning which are characteristic of bournonite. This specimen suggests that bournonite formed relatively late in the hypogene sequence and later than zinkenite and boulangerite.

Plagionite ($Pb_5Sb_8S_{17}$) has been reported from Oruro by various mineralogists, but it is a comparatively rare mineral. However, it may have been more abundant in the upper parts of the veins now worked out. Excellent crystals have been found lining vugs in the Purisima vein associated with meneghinite and franckeite. Plagionite was not found in the author's collection, but an excellent specimen was loaned to him by W. F. Foshag of the United States National Museum (No. C4926). This specimen is labelled "Socavon, Oruro, Bolivia." Probably "Socavon" refers to the Socavón de la Virgen where the Purisima vein was exposed and mined. The plagionite is in flat tabular crystals, 5 millimeters or more in diameter, and has a steel-gray color, metallic luster, and gray streak. It is intimately associated with rounded

[67] Berry, L. G., op. cit.
[68] Kozlowski, R. and Jaskolski, S., op. cit.

clusters of franckeite with which it appears to have been more or less contemporaneous in deposition.

An analysis by Zambonini [69] of a plagionite from the Purisima vein gave: Sb—38.30%; Pb—40.29%; S—21.43%; Ag—0.18%. Another by Pisani [70] gave: Sb—34.40%; Pb—44.20%; S—20.70%; Sn—0.62%; no Ag.

Semseyite ($Pb_9Sb_8S_{21}$) was not observed by the author and is believed to be a very rare mineral at Oruro. Spencer [71] described a silver-bearing variety from Oruro that he obtained from the Foote Mineral Company in Philadelphia. According to Spencer, semseyite occurs as iron-black crystals with a bright metallic lustre. The crystals were grouped in rosette-like groups and were associated with "plumosite." An analysis by Prior for Spencer gave: 52.9% Pb, 1.6% Ag, 24.8% Sb, 18.7% S, with a total of 98.0%. Sp. Gr. 5.82.

Meneghenite ($Pb_{13}Sb_7S_{23}$) was determined by Zambonini in ores from the Purisima vein where it was found in needles associated with plagionite. No other reference is made in the literature to this mineral, as far as is known, and, therefore, meneghenite must be considered an exceedingly rare mineral at Oruro.

Owyheeite ($Pb_5Ag_2Sb_6S_{15}$) was included by Lindgren and Abbott [72] in their list of Oruro minerals, but no comment concerning it was made. Owyheeite was not observed by the author, but, because its crystallography and physical properties are so similar to the other lead sulphosalts, it may very well have been overlooked.

Freieslebenite ($Pb_3Ag_2Sb_2S_{12}$) was mentioned by Spencer but was not observed by other writers on Oruro mineralogy. No details concerning it are available.

Chalcostibite ($CuSbS_2$) from the San José mine, Oruro, was described by Spencer. No other mention of its occurrence is found in the literature and it was not observed by the author. According to Spencer, the chalcostibite in his specimens was associated with andorite, stannite, quartz, and pyrite; it occurs in cavities in massive tetrahedrite as bright, steel-gray, tabular or blade-shaped crystals with brilliant metallic lustre, which are usually small, rarely reaching 1 cm. in length. The mineral has a perfect cleavage (010, perfect); (001) and (100) less so, and is deeply striated parallel to the 001 direction.

Galena (PbS) is relatively widespread at Oruro, although it usually occurs in small amounts. It was observed by the author in many veins including the Moropoto, San José, Purisima, and Grande veins, and has been reported in the Quintanilla, Nueva Atocha and Dolores veins. It was plentiful only in the Tetilla mine and in the lower parts of the Grande vein where it gradually increased in depth so that it is present in minable quantities.

Galena is usually associated with pyrite, franckeite and alunite, although in many places it occurs as galena alone, or as galena with a gangue of alunite.

[69] Zambonini, F., Beitraege zum Studium der natuerlichen Sulfasalze: Zeitschr. Krist., vol. 55, pp. 380–386, 1916.

[70] See Kozlowski, R. and Jaskolski, S., op. cit., p. 118.

[71] Spencer, L. J., Notes on some Bolivian minerals: Mineral. Mag., vol. 14, pp. 308–344, 1907.

[72] Lindgren, W. and Abbott, A. C., op. cit.

In the Grande and Quintanilla veins galena cements breccia fragments of quartz, pyrite and cassiterite.

Franckeite ($Pb_5Sn_3Sb_2S_{14}$) occurs sporadically in small amounts in the veins of the Socavón, San José, and La Colorada mines. Kozlowski and Jaskolski [73] reported that it has been observed in the Santo Cristo mine. The most abundant development of franckeite was found on the bottom levels of the Grande vein. Here, it forms well-defined veins, in association with galena, which vary from a few millimeters up to two centimeters wide. Apparently, franckeite increases in depth in the Grande vein, for it was observed in small amounts only on the upper levels. In places it coats the walls of vugs in pyrite, but more commonly it is in well-defined veins with galena running down the center of the Grande vein.

Franckeite is found in small, curving lamellae usually less than one millimeter across. Figure 54 illustrates the typical occurrence of this mineral where abundant. Franckeite where observed was associated with either galena, or plagionite, but veins of galena were found with little or no franckeite. Stannite and zinkenite have also been found with franckeite.

Galena and franckeite were the last of the primary (hypogene) metalliferous minerals deposited. Franckeite and galena have been observed both as replacement products of stannite and zinkenite, and in veins cutting these minerals as well as the quartz-pyrite-cassiterite ore. This conclusion does not agree entirely with the findings of Kozlowski and Jaskolski, for they observed that zinkenite was deposited after franckeite. The author found no lead sulphosalts later than franckeite. Crystals of galena are found perched on franckeite and in other places franckeite lamellae are found resting on crystallized galena. The age relations between these two minerals may be interpreted as overlapping with repeated deposition of both minerals.

Marcasite is found in small amounts in the Oruro veins. Lindgren regarded it as of supergene origin. Kozlowski and Jaskolski, on the other hand, distinguished two phases, one hypogene and the other supergene. They observed it far below the surface on the 340-meter level of the Bronce vein. The author is inclined to believe that marcasite, at least in part, is of hypogene origin, because of its presence in the veins far below the bottom of the oxidized zone and the water level, and because it is intimately associated with minerals of undoubted hypogene origin. Marcasite was not found in the pacos ores.

Marcasite usually forms a banded coating on other minerals. It is commonly found in radiating, fibrous growths which show very strong anisotropism in polished sections under the polarizing microscope. Marcasite is intimately associated with alunite and kaolinite. It appears to have been deposited after these minerals, but it may have overlapped them somewhat during precipitation (Figs. 55, 56).

Gangue.—The ores of the silver sulphosalt stage are remarkably free from gangue minerals. Quartz, alunite, dickite, and kaolinite are found in small amounts scattered through the ores of all the veins, and are always later than the silver sulphosalts. Alunite, dickite, and kaolinite were the last of the hypogene minerals to form, with the possible exception of marcasite.

[73] Kozlowski, R. and Jaskolski, S., op. cit.

Quartz is fairly common in small amounts and is usually found in the form of minute crystals, sometimes in radiating clusters, perched on tetrahedrite, galena, and other minerals lining the walls of cavities.

Traces of alunite and kaolinite are found throughout the mines, usually as vug and cavity fillings in porous ore. These two minerals commonly occur together and it is not possible to distinguish them except under the microscope with the use of index liquids. On the bottom levels of the Grande vein (-206 level, La Colorada mine) a well-defined vein of alunite and kaolinite with an average width of 20 cm was found in the center of a pyrite sulphosalt vein. The material composing this vein of gangue was soft and crumbly, and was saturated with water that gave a slight acid reaction. When dry, the alunite and kaolinite formed a compact, fine-grained mass, white in color, with a slight yellowish cast.

Zoning.—Detailed study of hypogene zoning has not been undertaken, and although a few general facts are known, much more work is necessary on this problem. Because many of the veins have been stoped extensively and no stope records of mineral distribution were kept, it is unlikely that the true zoning story will ever be thoroughly known or understood. However, observations made during the mapping of vein structure in 1937 and a study of assay records and of a suite of specimens collected at that time indicate that there is a considerable variation in the lateral and vertical distribution of metals and of mineral types, not only in individual veins, but also in the district as a whole.

In general, the tin and silver ores occur as well-defined shoots with assay limits in the more extensive quartz-pyrite veins. The high-grade tin ore shoots do not correspond in position with the centres of high-grade silver, although there is considerable overlapping of the two metals and they are usually mined together. Bodies of minable tin and silver ore when followed along the strike or dip gradually decrease in grade into material too low in tin or silver content to be minable under existing economic conditions. Many of these veins eventually die out in pyrite veinlets barren of silver or tin.

The Oruro veins are in general of higher grade on the upper levels immediately below the zone of oxidation than in depth. This is not because of supergene enrichment, for the silver-bearing minerals are predominantly tetrahedirte and andorite, and the tin-bearing mineral is predominantly cassiterite—minerals typical of hypogene rather than of supergene vein zones. The similarity in texture of the shallow level ores and those of the deeper levels also supports this conclusion.

In depth, the grade of tin decreases more rapidly than does that of silver, although the stronger, more persistent veins, such as the San Luis and Bronce veins, contain tin of minable grade to a lower level than do the weaker veins. The veins on the lower mine levels, in general below the -200 level, were mined chiefly for their silver content. This is particularly true of the San Luis, Grande, Bronce and Purisima veins. In the San José vein the tin content decreased abruptly below the -100 level (3,700 m elevation), but the grade of silver ore did not decrease appreciably below the -150 level (3,650 m elevation). The Grande vein was mined below the -200 level for its silver

and lead content, and in this particular vein, contrary to the usual behavior of Oruro veins, the silver content increased in depth at least as far down as the -290 level. Locally the tin content is fairly high, but this is where late veins of almost pure franckeite have cut the silver- and lead-bearing minerals. The deeper levels of the San Luis and Bronce veins, below the -300 level, were mined exclusively for silver.

Considering the district as a whole, it is apparent that the minerals of the silver-bearing sulphosalt stage were more persistent, both laterally and vertically, than were those of the quartz-pyrite-cassiterite stage. Not only do most of the veins pass from tin-silver to silver-bearing veins in depth, but also argentiferous galena veins with little or no tin occur outside of the centers of tin-silver mineralization. For example, the veins of the Tetilla mine, about one kilometer south of the San José and Itos mines, were composed of galena with barite and tetrahedrite.

The occurrence of the Oruro veins in clusters indicates that the "ore inlet" concept suggested by Locke, Billingsley and Schmitt [74] may be applicable here. If so, then each cluster might be considered to be related to a separate "ore inlet," and one would expect a zonal variation of mineral types about the four centers in the Oruro district. To some extent this is probably true; each cluster has a characteristic group of minerals, or if the same minerals are present in adjacent clusters, their relative proportions vary. However, lack of adequate data prevents definite conclusions on this aspect of the zonal picture. Locke's suggestion that zoning may be confused by overlapping of minerals from adjacent ore clusters, which are fed from separate inlets, appears to be confirmed at Oruro. Such overlapping results in a mineral distribution difficult to fathom, although the general paragenesis of the veins does not appear to have been affected.

Oxidized Ore Stage.—The ore bodies and ores of the oxidized zone have not been studied thoroughly by the author, but certain observations from a microscopic study of specimens collected in the field are worth recording. As far as is known, the silver ores of the oxidized zone are completely exhausted, and it is probable that their paragenesis will never be known.

The depth of oxidation in the Oruro district varies from 20 to 150 m below the present surface. The limit between the unaltered zone and the area affected by surficial alteration is an extremely irregular line. In general, due to high permeability, the veins are oxidized to a far greater depth than are the surrounding wall rocks. The normal position of the water table is unknown at the present time because of its artificial depression by pumping in the mine openings.

The principal minerals of the pacos zone are limonite, cassiterite, jarosite, quartz, and chalcedony. Locally, cerussite is abundant. The ores vary in color, but various shades of yellow, brown, and dark red are the most common. Generally, the pacos material is porous, loose, and incoherent with the various textures characteristic of oxidized ores such as vuggy, cellular, honeycombed; and clayey masses with incrustations and mamillary growths are usual.

[74] Locke, Augustus, Billingsley, P. R. and Schmitt, H. A., Some ideas on the occurrence of ore in the western United States: ECON. GEOL., vol. 29, pp. 560–576, 1934.

Cassiterite in the pacos ore is found in disseminated microscopic grains, but more commonly in banded texture coating altered wall rock. In places, it has formed a boxwork texture and where the banding texture is well developed forms the variety of cassiterite known as "wood tin." Figures 57 to 60 illustrate the textures of the pacos ore and especially cassiterite where it is abundant. In places, the bands of cassiterite have been broken and appear as a breccia in the sections.

Quartz in association with cassiterite is found in interlocking microscopic grains filling in around the cassiterite and commonly as a druse texture coating the cassiterite in euhedral crystals.

Jarosite and limonite usually coat and fill in around the cassiterite and quartz, and in many places, where cassiterite is absent, form large, irregular masses of loose, incoherent, earthy material.

Supergene vs. Hypogene Cassiterite in the Pacos Ores.—For two reasons, it is desirable to consider whether the cassiterite in the pacos ores is hypogene or supergene in origin. In the first place, the oxidized ores average 4–5 percent, whereas the primary ores average only 1–3 percent tin, and, in the second place, the banded and boxwork textures of cassiterite found in the oxidized ores are somewhat different from any textures found in the primary ores. Therefore, it is necessary to explain the increase in grade from primary to oxidized ore and the textural variations. Obviously, all of the cassiterite present was derived in one manner or another from the primary ore, but it is desirable to know what part secondary processes played in its concentration.

Three possible explanations of these phenomena are suggested: (1) The variations in grade and ore texture are due to primary zoning. That is, under near-surface conditions with a steep thermal gradient, rapid dumping took place from ascending solutions as the surface was approached. An increase in amount of tin precipitated and normal coating textures developed thereby. (2) Supergene enrichment took place by solution and redeposition of cassiterite by descending waters under oxidizing conditions. (3) Residual concentration of cassiterite occurred during oxidation and erosion of the vein outcrops. Removal of waste rock and minerals increased the relative proportion of tin per cubic foot. In this case, the textures are in part residual from the primary ore and in part due to deposition of cassiterite derived from the oxidation of stannite and franckeite. The evidence cited below indicates strongly that the third alternative is the correct one.

Undoubtedly, there is primary zoning in the veins, and it is known that the tin content of many veins decreases in depth. Probably the higher value of ore at the surface is due in part to this cause, but some reworking of the ores took place during oxidation.

It is unlikely that solution of cassiterite took place by descending surface waters. In the first place, there is no leached zone present which one would expect if solution and downward leaching had occurred. Also, alluvial tin is found in the gullies below the outcrops of the veins indicating that cassiterite was very resistant to solution and was durable enough to withstand transportation. This conclusion conforms to the general consensus of opinion on the

behavior of cassiterite in the major ore deposits of the world. Lindgren,[75] Emmons,[76] and Singewald [77] have clearly expressed this opinion. Furthermore, Lindgren and Abbott [78] stated explicitly, "We think it out of the question that quartz was formed during the period of oxidation when jarosite was deposited. We find no evidence of cassiterite being deposited during the oxidation, and believe that all of the cassiterite is residual hypogene material."

During oxidation, pyrite, the silver-bearing minerals, stannite, and probably franckeite were broken down. Silver was reprecipitated as cerargyrite and probably as other silver salts. Much limonite and jarosite formed. Cassiterite alone remained unattacked by surface solutions. Considerable slumping took place with decrease in volume, and residual concentration of the heavy, resistant minerals occurred. At the present time, loose, incoherent, gravelly aggregates of cassiterite mixed with limonite are found a few meters below the outcrops of the veins, in the veins, and in joints, fractures, and irregular masses. Therefore, residual concentration plus a higher original tin content account for the present grade of the pacos ores.

It is likely that the boxwork texture commonly found in the oxidized ore is at least in part residual from the primary ore. In a few places, banding which compares roughly with that in the pacos ore was found in ores deep in the mines. Also, the boxwork texture resembles very closely the "cockade" texture found in places in the deep levels of the mines. This develops where pyrite has coated resistant fragments of rock in the explosive breccia. However, it is a simple matter to substitute cassiterite for pyrite and obtain a similar texture. Also, under near-surface conditions with open, porous rocks, such a texture could form readily from ascending hydrothermal solutions.

The behavior of the sulphostannates, stannite and franckeite, in the oxidized zone is not definitely known. Possibly only small amounts of these minerals were present at the outcrops of the veins. Franckeite increases with depth in the Grande vein and stannite is found more commonly on the lower levels of the mines. Increase of these minerals in depth may be due to hypogene zoning, which may mean that the upper extent of the veins was relatively low in these minerals. Sulphosalts in an oxidizing environment with sulphuric acid derived from the oxidation of pyrite would undoubtedly break down to stannic sulphate from which SnO_2 would precipitate to form cassiterite. Lindgren [79] states that he considers it extremely probable that stannite on oxidation will yield colloidal SnO_2 solution. The wood tin found in the Oruro district could have been derived from this source. Also it is possible that some of the banded cassiterite, such as that illustrated in Figures 57 to 60 came from this source.

[75] Lindgren, W., Mineral Deposits, 4th ed., p. 872, New York, 1933.

[76] Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, pp. 398–402, 1917.

[77] Singewald, J. T., Jr., The problem of supergene cassiterite: Econ. Geol., vol. 24, pp. 343–364, 1929; also vol. 25, pp. 211, 218, 1930.

[78] Lindgren, W. and Abbott, A. C., The silver-tin deposits of Oruro, Bolivia: Econ. Geol., vol. 26, no. 5, p. 476, 1931.

[79] Lindgren, W., Mineral Deposits, 4th ed., p. 872, New York, 1933.

It is important to note in this connection that at Carguaicollo, Bolivia, Turneaure and Gibson [80] found that teallite in the zone of oxidation, although more resistant than the associated sulphides, was partly altered and ". . . under the microscope such partly altered teallite is seen to be replaced along the cleavage chiefly by anglesite, jarosite, plumbojarosite, and exceedingly fine-grained pale yellow cassiterite." Thus definite evidence is available that teallite breaks down in the zone of oxidation, and that the Sn goes into cassiterite. Franckeite and stannite were not found in the zone of oxidation at Oruro, but it seems probable that their behavior would be somewhat similar to that of the teallite at Carguaicollo.

It is probable that some of the banded cassiterite found near the surface at Oruro came from the breakdown of franckeite and stannite in the zone of oxidation. However, the presence in the hypogene ore of distinctly banded cassiterite with concentric growths and internal radiating fibers resembling "wood tin" (Figs. 57 to 60) indicates that most of the banded cassiterite in the zone of oxidation was primary. According to Turneaure,[81] ". . . similar banded, fibrous cassiterite at Llallagua is hypogene."

Therefore, it seems reasonable to conclude that the greater part of the banded cassiterite found in the pacos ores at Oruro is residual from the hypogene ores and that the banding (or colloform texture) is original. However, some of the material having this texture was probably derived from the breakdown of franckeite and stannite in the zone of oxidation. It is likely that a more detailed, comprehensive microscopic study of the pacos ores would establish this fact, and probably such a study would lead to the recognition of characteristics which would serve to distinguish banded cassiterite residual from the hypogene sulphide ores from wood tin derived from the breakdown of sulphostannates.

Summary.—Hypogene mineralization began in the Oruro district with hydrothermal alteration of the wall rocks. A widespread, relatively slight alteration resulted in the formation of sericite, and locally chlorite, in all of the intrusive igneous rocks of the district. Within the area of intense vein mineralization rock alteration was more intense; sericite and pyrite formed but without obliteration of the original rock texture. Adjacent to the veins rock alteration was intense and probably occurred concurrently with vein mineralization. The original rock was converted to an aggregate of sericite, quartz, and pyrite with complete obliteration of original rock texture. Locally tourmaline developed and where concentrated resulted in a greisen-like rock.

The early phase of hypogene vein mineralization resulted in massive, granular intergrowths of quartz, pyrite, cassiterite and a very small amount of arsenopyrite. These minerals formed by replacement of wall rock and by open-space filling and were deposited in both overlapping and successive relations. Probably quartz was deposited first, but continued to form during and

[80] Turneaure, F. S. and Gibson, Russell, Tin deposits of Carguaicollo, Bolivia: Am. Jour. Sci., vol. 243-A, Daly Volume, pp. 523–541, New Haven, Connecticut, 1945. (See particularly page 537.)

[81] Turneaure, F. S., Personal communication.

after the deposition of the other minerals of the early phase. Pyrite began to form before, and continued to form during, the deposition of cassiterite, and some formed after the precipitation of cassiterite had ceased.

Following the early stage of vein mineralization came a structural break. The early veins were fractured and reopened, and later-stage complex sulphosalts and sulphostannates carrying silver, lead, tin, antimony, and copper were formed. Evidence of a structural break separating the quartz-pyrite-cassiterite stage from the silver-bearing sulphosalt stage consists of: (1) widespread brecciation of the early vein minerals; (2) minerals of the second stage in well-defined veins, 5 to 15 centimeters wide, running parallel or at right angles to the early veins and in places offsetting them; and (3) crude banding in veins, with slivers of altered country rock separating bands or veinlets that carry minerals of the first or second stage or of both stages. A small amount of sphalerite and chalcopyrite, followed by more abundant stannite, inaugurated mineral formation of the second stage. These were followed in overlapping relations by freibergite, andorite, boulangerite, zinkenite, bournonite, and other sulphosalts. Galena and franckeite were among the last minerals of this stage to form and they commonly occupy individual veins which cut the earlier mineralization. Late-stage alteration of wall rock to alunite and kaolinite took place locally, and in places these minerals formed as gangue minerals in the veins. They appear to be as abundant on the lower levels of the mines as on the upper levels, and in fact, in certain veins, may increase in abundance with depth. This distribution clearly indicates that these two minerals are hypogene rather than supergene in origin. Marcasite appears to be the last sulphide mineral to have been precipitated and, like alunite and kaolinite, probably indicates a late acid character of the ore solutions from which it was precipitated.

Following hypogene mineralization erosion and oxidation attacked the upper extent of the veins. It is possible that the veins extended to the surface and that hot springs and associated deposits may have formed, but if so all trace of them has been removed. During oxidation, pyrite, the silver-and lead-bearing sulphosalts, stannite, and probably franckeite were broken down. Silver was reprecipitated as cerargyrite and native silver; much limonite and jarosite formed. Cassiterite alone remained unattacked by surface solutions and other agencies. Residual concentration of cassiterite occurred, but some cassiterite was removed by erosion and accumulated as placer tin in the gullies that radiate from the mineralized area. The breakdown of stannite and franckeite probably resulted in the deposition of a small amount of wood tin.

GENESIS OF THE ORURO DEPOSITS.

Age of the Deposits.—It is probable that the ore bodies at Oruro were deposited soon after the intrusion of the quartz latite porphyry bodies and formation of the San José breccia. Unfortunately, the exact age of the igneous rocks themselves is uncertain. Geologic and physiographic features in the Cerros de Oruro are not sufficiently complete to date igneous intrusion, but it may be possible to correlate these features with those in other areas in cen-

tral Bolivia where fossiliferous sediments and other diagnostic elements have been found.

It has been shown by Ahlfeld,[82] Smulikowski and Kozlowski,[83] and other students of Bolivian geology that the Oruro intrusives are members of a petrographic province which extends southward many kilometers from the Cerros de Oruro. In size, composition, and association with tin-silver ore, they are similar to many intrusives in central and southern Bolivia. The age of these intrusives has not been established except at Potosí, where rhyolite porphyry of the Cerro Rico de Potosí intrudes fossil plant-bearing beds reported by Berry [84] to be Pliocene in age. These fossils have been studied in detail by Berry who concluded ". . . that the flora is Pliocene in age and that the major elevation of the eastern Andes of Bolivia and the high plateau took place in late Pliocene and throughout the Pleistocene and that the extensive mineralization of this region also took place during this same period."

Steinmann,[85] Ahlfeld,[86] and recently Walker [87] questioned Berry's conclusions. Steinmann held that knowledge of the distribution of fossil plants in the Andes Mountains is not complete enough to allow such precise dating and suggested that the flora is probably late Miocene, but may be Oligocene or Pliocene. On the other hand, Ahlfeld concluded that the age of the tin-bearing intrusive and effusive igneous rocks of Bolivia is fixed as belonging to the earlier part of the Tertiary, as are the ". . . Andine granites of Peru, and that they were erupted in connection with the Second Main Folding of the Andes." Moreover, Ahlfeld states, "The late Pliocene age, assumed on the basis of the plant beds of Potosi, is probably incorrect."

Walker's reasons for questioning Berry's conclusions may be summarized as follows:

At various places on the Altiplano and in the eastern Cordillera a group of sediments, known as the Puna Beds, liè horizontally upon an erosion surface that truncates the Andean folds. The Puna Beds contain a mammalian fauna that has been established as upper Pliocene in age. Moreover, the erosion surface is believed to be a remnant of the extensive Puna peneplain that truncates the folded Paleozoic rocks, the granitic batholith of northern Bolivia and the fossil-flora-bearing beds of Coro Coro, and is believed on the basis of fossil evidence in southern Peru to be Pliocene.

If Berry's Pliocene dating of the Potosí flora is correct, then it is necessary to assign the Andes folding, the igneous intrusions of northern and central Bolivia, and the cutting of the Puna surface to the interval between the middle

[82] Ahlfeld, F., Los yacimientos minerales de Bolivia, La Paz, 1941.

[83] Smulikowski, K. and Koslowski, R., Les rockes éruptives des Andes en Bolivie: Arch. Min. Soc. Sci. Var., vol. 10, pp. 121, 242, 1934.

[84] Berry, E. W., Fossil plants from Bolivia and their bearing upon the age of the eastern Andes: U. S. Nat. Mus. Proc., vol. 54, pp. 103–164, III, Washington, 1917.

[85] Steinmann, G., Geologie von Peru, Heidelberg, 448 pp. (R. Stappenbeck Nutzstoffe, 318–393), Spanish translation, 1930.

[86] Ahlfeld, F., Über das Alter de Zinnbringenden Magmengesteine Boliviens (on the age of the stanniferous igneous rocks of Bolivia): Zentralblatt f. Min., Abt. A, no. 2, pp. 34–38, 1937.

[87] Walker, Eugene H., Personal communication. This problem is discussed in detail in Walker's doctoral dissertation at Harvard University. He very generously loaned me his chapter on "Physiographic History and the Dating of Events," and gave me permission to quote him here.

and upper Pliocene. Walker believes with good reason that this interval is too short in duration to allow time for these geologic events to occur and that probably Berry's dating is wrong. Evidence is accumulating, therefore, which tends to indicate that the igneous intrusions and associated mineralization of central Bolivia occurred somewhat earlier than Berry's estimate, probably late Miocene.

Age in itself is rarely a key to the nature of geologic environment during ore deposition; but ore deposits of Tertiary age found in volcanic rocks, or in association with shallow-seated intrusives, are generally classed by Lindgren as epithermal, with an implication of low temperature and low-pressure conditions during ore deposition.

Source of the Ore Solution.—The veins at Oruro are found in and contiguous to closely spaced quartz latite porphyry stocks, an association which is duplicated in many places in central and southern Bolivia; thereby disclosing a genetic relationship more fundamental than simple structural control exerted by fractures in a relatively brittle rock which served to localize ore deposition. In these mining districts, the facts clearly indicate that the sequence of intrusion, rock failure, and mineralization was limited to a relatively short period of time; and it follows that crystallization of magma, fracturing of rocks and mineralization probably took place in essentially the same environment.

From the general association of tin and tin-silver-bearing veins of central and southern Bolivia with near-surface intrusives that have volcanic affinities and a similar composition, it is logical to conclude that the ore-bearing solutions were derived from a common magmatic source. If there is any merit at all in present theories of ore genesis, and if the spatial relation of igneous intrusives and ore deposits is significant, then it must follow that the quartz latite plutons of Oruro and the tin-silver-bearing veins were derived from a common magmatic source. One can only speculate concerning this source, but it seems likely that it is related to an underlying zone of magmatic activity which gave rise to Llallagua, Potosi, and the many other ore deposits of the central and southern Bolivian metallogenetic province.

Depth of Vein Formation.—It is clear from the general geology of the Oruro district that the veins now exposed were formed at a comparatively shallow depth. The nature of the igneous intrusive bodies, particularly their shape and relations to the enclosing rocks, suggest that they are near-surface intrusions. Moreover, the porphyritic texture of the igneous rock is suggestive of a shallow-seated environment during crystallization. The Oruro fracture pattern, intricate in detail, irregular, lacking persistence, and increasing in complexity toward the surface, is indicative of rupture under light load and under near-surface conditions. Also the ore textures, open, vuggy with many druses and delicate banding, are of the type commonly attributed to shallow-seated ore deposition. The change in tenor of the ore, rich in tin near the present surface and decreasing rapidly in tin content in depth, and the behavior of the silver ore shoots indicate rapid precipitation under near-surface conditions. Therefore it may be concluded that not only do the igneous rocks and the fracture system indicate that a shallow-seated environment was provided for ore deposition, but also the vein products themselves indicate deposi-

tion in a near-surface environment. Valid as this conclusion is, however, for purposes of genetic classification and for an appraisal of the temperature-pressure conditions existing during ore deposition, it is highly desirable to know in quantitative, as well as qualitative terms, the approximate depth at which the ore was deposited.

In reviewing the genesis of the Oruro ore deposit, Lindgren [88] wrote that ". . . the depth of vein material removed by erosion from the outcrops of the veins, since their formation may not have been more than 1000 feet." Erosion at Potosí was estimated at a similar amount [89] so the veins now exposed at Potosí would have been formed at approximately 1,000 feet below the then-existing surface. Unfortunately, Lindgren did not give the data or explain the reasoning on which he based his Oruro estimate; but concerning Potosí, he stated that ". . . the texture of the rock suggests a near-surface intrusion and considering the physiographic features it would seem that the summit of the mountain (Cerro de Rico) could not have been more than 1,000 feet below the surface at the time of ore formation." Probably Lindgren's Oruro estimate was based on the same type of evidence. For the ore deposits at Llallagua, Turneaure [90] estimated, on the basis of physiography and the thickness of volcanic formations genetically associated with the Salvadora stock, that a minimum of 3,000 feet appears reasonable for the thickness of the cover at the time of ore deposition. The general conclusion, therefore, appears justified that the tin and tin-silver deposits of central Bolivia, particularly those at Oruro, Potosí, and Llallagua, formed at relatively shallow depth; the present outcrops are probably from 500 to 3,000 or 4,000 feet below the surface existing at the time of ore deposition. At Oruro the amount of material removed by erosion from the crest of the Cerros de Oruro since the veins were formed may not have been more than 500 feet and certainly was not over 2,000 feet. More precise quantitative estimates than these are not justified on the basis of the scant knowledge and understanding of the local geology at Oruro and the regional geology and physiographic history of central Bolivia.

Temperature and Pressure.—Temperature and pressure, through their profound influence on solubility, play important roles in controlling the deposition of minerals from hydrothermal solutions. Considerations of ore genesis and vein classification are based in part on an appraisal of these two factors. However, our knowledge and understanding of the physical conditions under which ore deposition takes place is rudimentary and conclusions based on inferred temperature or pressure must be only tentative.

From the shallow depth at which the Oruro veins formed it is readily inferred that, if pressure may be considered a function of depth, the pressure existing during ore deposition was low. This conclusion is in line with Lindgren's concept of depth-pressure relations and may be correct if the only source of pressure is that caused by the weight or "head" of the overlying rock

[88] Lindgren, W. and Abbott, A. C., The tin-silver deposits of Oruro, Bolivia: ECON. GEOL., vol. 26, pp. 453–478, 1931.

[89] Lindgren, W. and Creveling, J. G., The ores of Potosí, Bolivia: ECON. GEOL., vol. 23, pp. 233–262, 1928.

[90] Turneaure, F. S., The tin deposits of Llallagua, Bolivia: ECON. GEOL., vol. 30, pp. 14–190, 1935.

column. It is possible, however, that other causes may have been operative which tended to increase pressure within the channelways followed by ore solutions.

If the mechanism that drives ore solutions from the magmatic source toward the surface is caused by forces other than, or in addition to, pressure derived from the weight of superincumbent rocks, it seems possible that the pressure existing at the locus of ore deposition may be greater than is generally assumed. Observational or quantitative data to support this supposition, as far as the author is aware, are not available. However, theoretical considerations suggest that it may be true. For example, in addition to the weight of superincumbent rocks, another possible source of pressure is the crystallization of magma in accordance with the Morey principle.[91] Pressure developed in a magma as a result of crystallization may provide a driving mechanism in addition to hydrostatic "head," and so increase the internal pressure in the ore solutions that relatively high pressure would exist near the surface.

The main objection to the use of the Morey principle as a propelling mechanism was pointed out by Graton,[92] who wrote as follows: ". . . although great vapor pressure can develop and exist by this means without the development of any gas phase, any utilization of this pressure in the way of expelling fluid from the system would instantly generate a gas phase in amount corresponding to such utilization. . . ." Graton, as well as many other students of ore deposition, believes that an abundant gas phase ordinarily does not exist at depth. However, if, as many geochemists believe, an abundant gas phase does develop, then no difficulty is encountered in utilizing Morey's concept for the generation of high pressure.

The distance from the magma source to the surface, friction, and the nature and tortuosity of the channelways followed by the ascending ore solutions tend to diminish and dissipate pressure on the rising solutions. It is difficult to evaluate these influences quantitatively, but undoubtedly in many cases they are sufficient to reduce pressure gradually so that when the solutions approach the surface, pressures are essentially normal. On the other hand, in certain cases, especially where the magmatic source is relatively near the surface, high pressure continues nearly to the surface itself, fracturing becomes intense and pressures are released on a wholesale scale.

The conclusion may be justified, therefore, that pressure may not always be a function of depth and in certain cases, such as at Oruro, high pressures may have existed relatively near the surface, although it is recognized that the source of the pressure is not known with assurance. Of course, as rising solutions under high pressure approached the surface where fracturing is pronounced, there undoubtedly was a sudden release of pressure. Accompanying this pressure release there is probably an abrupt transformation of part of the liquid phase into the gas phase. This transformation probably plays an im-

[91] Morey, George W., The development of pressure in magma as a result of crystallization: Washington Acad. Sci. Jour., vol. 12, no. 9, pp. 219–230, 1922.

[92] Graton, L. C., Nature of the ore-forming fluid: ECON. GEOL., vol. 35, Supplement no. 2, p. 324, March–April 1940.

portant part in certain types of mineral deposition and probably accounts for certain features of mineral paragenesis and telescoping that are considered anomalous.

Concerning the temperature conditions at Oruro during ore deposition, it seems probable, for reasons that will be brought out later, that the shallow-seated intrusives provided a warm environment and that the ore channelways may thus have been pre-heated at the time of ore deposition. This would be in contrast to the usual situation where ore solutions are believed to have been introduced into cold rocks or into rocks with a normal temperature gradient. Hot effusive rocks and shallow-seated intrusives undoubtedly create for considerable time abnormally steep temperature gradients. If the injection of these rocks took place shortly before the ore channelways were created and the ore solutions were introduced, as appears to have been the case at Oruro, the hot rocks would have provided a relatively hot environment, and in this case the ore channelways might be said to have been "pre-heated." Such a condition undoubtedly influences mineral deposition profoundly and may account for the "telescoped" characteristics of the Oruro deposit and of other deposits.

The minerals of the first stage at Oruro, quartz, pyrite, and cassiterite, with minor amounts of arsenopyrite and tourmaline, are probably persistent over a wide intensity range, and, therefore, are not in themselves diagnostic of temperature conditions during ore deposition. Ore deposition, undoubtedly, took place well below the melting points of all of these minerals. Quartz is the only one of the group that has an inversion point (α to β quartz at 575° C at one atmosphere), but it may be safely assumed that its formation took place well below this point. Other geologic thermometers, such as points of dissociation, exsolution, recrystallization, the behavior of liquid inclusions and changes in physical properties, either are lacking in this district or no data are available concerning them. The only possible method of determining temperature conditions, therefore, appears to be an appraisal of the minerals on the basis of their general association with other minerals that are diagnostic. Only tourmaline and cassiterite offer some hope in this respect; the others occur too widely, with too large a group of associated minerals and in too great a variety of geologic environments to be useful.

Tourmaline is generally believed to be a high-temperature mineral, indicative of high-temperature conditions during ore deposition, because of its usual occurrence in pegmatites; in contact metamorphic aureoles around intrusive bodies; as an original constituent of granites and pegmatites; and its general association with quartz, albite, microcline, and muscovite. Tourmaline, like topaz, contains a volatile constituent and, according to Lindgren,[93] requires pressure and the presence of mineralizers for its formation. If the occurrence of tourmaline and its common mineral associations are significant, then the hydrothermal temperature at Oruro was relatively high during the early stage of mineral deposition.

Cassiterite is the most distinctive mineral of the group and usually is considered to have formed in a relatively high temperature environment and

[93] Lindgren, W., Mineral Deposits, New York, 1933, p. 638.

at great depth. Actually, its field of stability is not known,[94] and it is found in a wide range of geologic environments and in association with a number of minerals. Ferguson and Bateman [95] state that cassiterite is capable of formation under a variety of conditions: as an original constituent of granite and granite pegmatites; as a result of pneumatolysis; as a result of contact metamorphism; as a true hydrothermal product, and as a deposit from hot springs at atmospheric pressure. The characteristic occurrence of cassiterite in commercial mineral deposits is in high-temperature hydrothermal veins or as replacement deposits that are genetically associated with highly siliceous igneous rocks, usually granite or quartz porphyry. Besides greisen, the associated minerals are usually wolframite, molybdenite, arsenopyrite, bismuth, bismuthinite, with much less abundant pyrite, pyrrhotite, chalcopyrite, galena, and sphalerite.

Although cassiterite is extremely resistant to weathering, it is sometimes found as "wood tin," a radial, fibrous variety, in places ascribed to secondary processes. Regardless of whether the SnO_2 is derived from the breakdown of cassiterite or from other tin-bearing minerals, there is no doubt that cassiterite itself is precipitated under temperature and pressure conditions existing in the zone of oxidation.

Thus cassiterite, although commonly cited as indicative of high-temperature mineralization, can hardly be called diagnostic. However, its common association with high-temperature minerals suggests that this is the more normal environment. It may be significant that the cassiterite at Oruro differs considerably in appearance from the rich brown varieties, commonly with zonal growths and good crystal outlines, that are commonly found in high-temperature veins. The cassiterite at Oruro is a pale to colorless mineral with a very fine granular texture and without zonal growths or crystal outline. Whether the variations in color, crystal growth and other properties are caused by impurities such as iron, tantalum, or columbium, or by temperature and pressure conditions during formation is unknown.[96]

If it should be true that high pressure, as well as high temperature, existed relatively near the surface during hypogene mineralization at Oruro, then an explanation would be available as to why cassiterite, normally a deep, hypothermal product, is formed at Oruro, Llallagua and Potosí under near-surface conditions.

The minerals of the second stage, sphalerite, chalcopyrite, stannite, tetrahedrite, andorite, zinkenite, boulangerite, bournonite, franckeite, and galena, do not give us precise data for fixing the temperature range during ore deposition. Like the minerals of the first stage, they formed far below their melting points; and other properties that would be of use as geologic thermometers are lacking. As a group, however, they are generally believed to indicate moderate-to low-temperature conditions during deposition. Probably the earlier members of the group to form—chalcopyrite, sphalerite and stannite—in-

[94] Lindgren, W. and Creveling, J. G., The ores of Potosí, Bolivia: ECON. GEOL., vol. 23, p. 260, 1928.

[95] Ferguson, H. G. and Bateman, A. M., Geologic features of tin deposits: ECON. GEOL., vol. 7, pp. 209–262, 1912.

[96] Palache, C., et al., Dana's System of Mineralogy, vol. 1, p. 580, 1944.

dicate somewhat higher temperatures than later minerals—andorite, boulangerite, jamsonite, zinkenite, and bournonite. Alunite, one of the last minerals to be deposited from hypogene solutions, has been reproduced at temperatures of 65° C, 100° C and 200° C.[97]

It is clear that the minerals of the Oruro ore deposit do not give us precise temperature data, but from the common association of the minerals with those that are diagnostic in other districts, and the usual interpretation that is placed on the group, it is inferred that the quartz, pyrite, and cassiterite mineralization with minor tourmaline and arsenopyrite began to form under moderate to high temperature conditions, perhaps 300°C to 400°C. Following vein fracturing and reopening, minerals of the second stage were deposited. Sphalerite, chalcopyrite, stannite, freibergite, andorite, sulphosalts of lead and antimony, franckeite, galena, and, finally, kaoline, alunite, and marcasite were deposited, as the temperature decreased to a point below 300° C, possibly as low as 100° C.

Although the conclusion is based on mineral association and geologic opinion rather than on diagnostic physical and chemical properties of the minerals themselves, we may conclude that, if the minerals present are at all indicative of the inferred temperatures, ore deposition began at Oruro at a moderate to high temperature and dropped to a fairly low figure before mineral deposition ceased. If this is true, then the minerals of the second stage were deposited under considerably less intense temperature conditions than were the minerals of the first stage.

The Ore Solutions.—Some clues to the nature of the hydrothermal solutions from which the metals of the Oruro deposits were precipitated may be found by a study of the ore mineralogy and the products of wall-rock alteration.

Adjacent to the veins, the porphyry is an aggregate of quartz, sericite, pyrite, with minor alunite, kaolinite and dickite. With distance from the ore channels, the products of alteration decrease until the rock is only slightly changed. In a few centimeters, kaolinite, dickite, and alunite disappear; secondary quartz is not found beyond a few meters; farther away pyrite gradually becomes scarce. Sericite is widespread throughout the district.

Sericitization results in the addition of potassium and loss of calcium, sodium, and magnesium. Aluminum remains constant. No reliable analyses are available to check these changes, but data from many districts where sericite replaces minerals in rocks of intermediate composition indicate that these are the usual changes. Sericite is usually considered to be a product of alkaline solutions rich in carbon dioxide which carry some potassium. Schmedeman[98] reviewed criticaly the sericite problem and concluded that: ". . . seri-

[97] Leonard, R. J., Hydrothermal alteration of certain silicate minerals: Econ. Geol., vol. 22, pp. 18–43, 1927.

[98] Schmedeman, O. C., Interrelated problems of volcanic activity and ore genesis: Doctoral Thesis, Harvard University, 1937.

Following Schmedeman, an acid solution is considered in this discussion as a "solution containing one or more of the following strong acids: hydrochloric, hydrofluoric, or sulphuric. An alkaline solution is defined as one containing no free strong acid, though it may contain one or more of the weak acids: silicic, hydrosulphuric, carbonic, or boric." (See page 8.)

cite as a mineral is not indicative of either alkaline or acid attack, but it probably *forms* (when potash is added) only from alkaline or weakly acid solutions." It seems likely that unless the K was combined with a strongly acid radical like a halogen, the strong alkaline character of the K ion would make the solution itself alkaline in proportion to its K content. We may conclude, therefore, that where sericite is formed, the waters are probably alkaline.

Pyrite is abundant in the rocks which enclose the ore bodies. In this connection, the observations of Day and Allen [99] at Lassen Peak, Calif., are instructive. They found that distinctly crystalline pyrite was confined to deposits associated with acid springs, whereas all the minerals referred to as pyrite in the alkaline spring deposits were of cryptocrystalline or amorphous nature. Day and Allen found that: "The conditions in the springs are strikingly similar to those found in the laboratory to be essential to the formation of pyrite, namely, the coexistence of ferrous salt, hydrogen sulphide, and sulphur." Later work at Yellowstone National Park by Allen and Day [100] tended to confirm this conclusion. It was found that pyrite formed over a wide temperature range as a secondary precipitate in many springs of the acid areas where ferrous salts came in contact with hydrogen sulphide and sulphur.

Experimental work has shown that pyrite may form in various ways, including the action of sulphur on ferrous sulphide in weakly acid, nearly neutral or alkaline solutions.[101] It is safe to conclude, therefore, in view of Allen and Day's observation and the experimental work, that pyrite is not definitely diagnostic of either alkaline, neutral, or acid solutions.

Moderate silicification and mild development of kaolinite, dickite, and alunite, which in part replace sericite, in the rocks immediately adjacent to the veins are strong evidence of attack by acid solutions. Several authorities have reviewed the alunite and kaolin problem.[102] All agree that development of these minerals necessitates a solution bearing sulphuric acid.

We may conclude, therefore, that the solutions which caused rock alteration at Oruro were originally alkaline and resulted in the development of sericite and pyrite, but toward the end of the mineralizing period became acid and small amounts of alunite and kaolinite were deposited as replacement products.

The interpretation of the vein minerals is more difficult and leads to less satisfactory results. Probably the early solutions coursing through the

[99] Day, A. L. and Allen, E. T., The volcanic activity and hot springs of Lassen Peak: Carnegie Inst. Washington Pub. 360, pp. 137, 138, 1925.

[100] Allen E. T. and Day, A. L., Hot springs of the Yellowstone National Park: Carnegie Inst. Washington, Pub. 466, p. 17, 1935.

[101] Allen, E. T., Crenshaw, J. L. and Johnston, John, The mineral sulphides of iron: Am. Jour. Sci., 4th Series, vol. 33, no. 195, p. 169, March 1912.

[102] Graton, L. C. and Bowditch, S. I., Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: ECON. GEOL., vol. 31, pp. 651–698, 1936.

Schmedeman, O. C., op. cit.

Burbank, W. S., Geology and ore deposits of the Bonanza District, Colorado: U. S. Geol. Survey Prof. Paper 169, pp. 82–83, 1932.

Graton, L. C., Nature of the ore-forming fluid: ECON. GEOL., vol. 35, pp. 331–336, 1940.

Butler, B. S., Primary (hypogene) sulphate minerals in ore deposits: ECON. GEOL., vol. 14, no. 8, pp. 581–609, 1919.

channelways were relatively simple. Quartz, pyrite, and cassiterite were deposited in open spaces with some replacement of the adjoining wall rock.

It is difficult to decide in what manner the tin was carried in the solutions. Since Daubrée first synthesized cassiterite and demonstrated that SnO_2 was formed by the reaction of SnF_4 with water, it has generally been inferred that tin is transported in ore solutions as the fluoride or chloride. However, the absence of chlorine-or fluorine-bearing minerals in the Oruro veins suggests that it was not transported in this way. Besides $SnCl_2$ and SnF_4, tin is soluble in acid solutions as $SnSO_4$ and as $Sn(NO_3)_2$ and in alkaline solutions as K_2SnO_3. One can only speculate as to whether or not the tin was transported in one or more of these compounds. The presence of cassiterite in colloform texture common in the Oruro ores is certain to lead to an interpretation by some students of ore geology that it was transported as a colloid. In a paper published in 1936, Lindgren [103] wrote as follows: "When we consider that cassiterite is commonly present in coloform aggregates, in epithermal and mesothermal deposits, it seems more likely that it enters into the neutralized emanations as a solution, either of SnO_2 or of α or β stannic acid, and that the SnO_2 is deposited by coagulation of such solutions." However, the objections to the transportation and deposition of cassiterite, or other mineral-forming compounds, in the colloidal state are so convincing, even when special mechanisms of precipitation are called on to avoid the substantial shrinkage involved when layers of colloidal SnO_2 or other compounds are converted into fibrous crystalline anhydrous cassiterite, that it seems unlikely that colloids play a part in the process of mineralization.

It is apparent that tin can readily be transported in a variety of ways, but lacking conclusive evidence, perhaps it is better to admit frankly that at present the actual method of transportation is unknown. The behavior of SnO_2 may be very similar to that of SiO_2; when details of silica transportation and deposition are known, we may better understand SnO_2.

Minor but widespread cracking and reopening of the ore channelways followed the cessation in deposition of minerals of the early stage. The resultant increase in permeability facilitated the continued flow of ore solutions, and second-stage minerals were deposited in the newly created fractures. In places, however, the later solutions spread into the quartz-pyrite-cassiterite ore, for locally these minerals are replaced by second-stage minerals and in many places second-stage minerals are found coating the walls of vugs in the early ore. Small amounts of chalcopyrite and sphalerite were the first of the second-stage minerals to be deposited. Tin remained in solution, but probably the stability field of cassiterite had passed with lowering temperature and pressure, and stannite, and later franckeite were precipitated in its place. Lead-antimony sulphosalts bearing silver were deposited in large amounts along the reopened veins. Minor fracturing continued throughout this period, for many of the very late minerals, particularly galena and franckeite, follow individual fractures which cut the older vein minerals in longitudinal breaks that follow the center of older veins. Finally, kaolinite, alunite, and dickite with marcasite

[103] Lindgren, W., Succession of minerals and temperatures of formation in ore deposits of magmatic affiliation: Am. Inst. Min. Met. Eng. Tech. Pub. no. 713, 1936.

were precipitated locally at the end of the mineralizing period, both in the veins and in the wall rocks.

The change in mineralogy and texture that followed intermineralization fracturing and vein reopening, structurally separating the early quartz-pyrite-cassiterite stage from the later silver-bearing sulphosalt stage, was originally interpreted by the author to indicate a pause or period of quiescence between the two stages, and, with renewal of emanations from depth, a fundamental change in the character of ore solutions at the source. The early solutions evidently carried Fe, Sn, S, and As, whereas the later solutions carried, in addition to these elements (except As), Cu, Pb, Zn, Ag, and Sb. Moreover, the minerals deposited, and particularly the ore textures, are strikingly different.

It is, of course, exceedingly difficult to prove that such a pause occurred, or that the ore solutions changed fundamentally at their source. It is quite possible that all the elements were present in the ore solutions throughout the hypogene epoch, and that the change in mineralogy and textures is a reflection of change in physico-chemical environment.

The fundamental problem at issue here is concerned directly with the explanation of mineral sequence in general. Is this sequence, found in most hypogene deposits, due to changes in the ore solution at the source or to changes in physico-chemical conditions which bring on and control mineral deposition? Of the two possibilities, the latter meets with considerably less difficulty on theoretical grounds. At Oruro, following the intermineralization fracturing, there probably was an appreciable change in temperature-pressure conditions. This change was probably sufficient to explain the changes that occurred in the Oruro veins. Although the author is reluctant to abandon entirely the idea that a fundamental change occurred in the ore solutions at the source, the weight of theoretical evidence is against the idea.

We have no precise or direct information on the nature of the solutions or the manner in which the minerals of the second stage were transported. Following Lindgren's idea, it may be that the solutions were neutral to slightly alkaline. At the end of the period, when alunite and kaolinite were deposited, they were distinctly acid in reaction.

The evidence from both wall-rock alteration and the vein minerals indicates that the ore solutions were alkaline at the beginning of the mineralizing period. Probably they gradually became neutral, then slightly acid, and finally, at the end of their circulation, were distinctly acid in reaction. The pronounced acidity probably did not develop until very late in the vein history when alunite, kaolinite, and dickite formed distinct veinlets cutting the sulphide ore or filling many of the remaining pores and vugs.

The reasons for this change in the ore solutions from alkaline to acid are not clear. Any attempt to find an answer to this problem, like that of the mineral sequence, must of necessity touch on some of the most fundamental problems in ore geology, particularly (1) the nature of the hydrothermal solution as it leaves the magmatic source, and (2) the changes that it undergoes in passing upward toward the surface. These problems are far too complex and involve too many assumptions to be treated at length here; only a

few pertinent comments will be made, therefore, for whatever bearing the Oruro occurrence may have on the broader problem of ore genesis.

The change from alkaline to acid conditions, noted at Oruro, has been observed in several other mining camps, notably Goldfield, Nevada, the San Juans in Colorado, Cerro de Pasco, Peru, and in Bolivia at Llallagua and Potosí. Ransome, Butler, Burbank, Lindgren, Graton and Bowditch, and Schmedeman, to the author's knowledge, have discussed this problem, and three reasons or methods have been advanced to explain the phenomenon. These are concerned primarily with ways of generating H_2SO_4 in alkaline ore solutions and the formation of alunite.[104]

At Oruro the change in character of the ore solutions and the origin of alunite and kaolinite is definitely hypogene in nature and is unrelated to surface oxidation or to the intermingling of hypogene solutions with downward circulating water. Moreover, the lack of ferric minerals in the ores or wall rocks indicates that Butler's theory that sulphur or sulphur-bearing compounds formed as a result of the oxidizing effect of ferric minerals is not tenable.

Because the greater bulk of alunite, kaolinite, and dickite at Oruro occurs as gangue minerals in the sulphide ores or discreet veins cutting this ore, rather than as a product of rock alteration, it is apparent that the source of solutions giving rise to these minerals was somewhere below the deepest levels of the mine. This source may have been either a direct magmatic emanation of sulphuric acid, or a change in nature of the hypogene solutions. The methods proposed by Graton and Bowditch [105] for the development of late acid solutions and alunite at Cerro de Pasco fit the facts at Oruro admirably. According to Graton, ore solutions, originally alkaline, may become acid through the generation of sulphuric acid "by the oxidizing reaction of water on some form of sulphur" originally abundant in the solutions. Decrease of pressure with continued high temperature in pre-heated channelways would tend to facilitate this reaction. In this respect, at least, the behavior of ore solutions at Cerro de Pasco seems to have been paralleled at Oruro.

Conclusions on Ore Genesis.—Complex as the mineralizing process is, with its many ramifications and unsolved problems, it is nevertheless clear that this is but one phase of a complicated geologic process which includes igneous intrusion and extrusion, brecciation, pre-mineral and intermineralization fracturing, wall-rock alteration, and vein mineralization. It is likely that this is a more or less continuous process, probably with significant pauses, and certainly with changes with time. All of the elements of this process are readily observed at Oruro.

Vein formation and particularly ore genesis are directly affected by the geologic events that precede and accompany circulation of ore solutions. At Oruro the ore solutions were probably injected into a relatively hot environment with pre-heated channelways and with relatively steep temperature gradient. If mineral deposition depends primarily on temperature change and

[104] For details see Graton, L. C. and Bowditch, S. I., Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: Econ. Geol., vol. 31, no. 7, pp. 651–698, 1936.

[105] Graton, L. C. and Bowditch, S. I., op. cit.

heat loss, then a warm environment would have the effect of retarding mineral deposition so minerals normally deposited at considerable depth would actually form near the surface. This may explain the presence in a near-surface environment of minerals and textures characteristic of a deeper, more intense depth zone.

In addition to the effect of a pre-heated environment, the process of mineral deposition at Oruro was complicated by intermineralization fracturing and vein reopening. The effect of vein reopening would probably be (1) to maintain and perhaps greatly increase permeability of the vein channelways, and (2) to cause an appreciable decrease in pressure (back pressure).[106] In a near-surface environment the sudden release of pressure probably would not be accompanied by a correspondingly rapid decrease in temperature. If it is assumed that the ore solutions were hot liquids of alkaline reaction, then, under these conditions, the solutions would tend to boil with the liberation of gas. Moreover, the solubility conditions in the solutions would change greatly and the rate of mineral deposition would probably accelerate; the alkaline-acid relations would probably be such that the gas phase would have an acid reaction; the stability range of many of the minerals would be greatly affected.

Pre-heated ore-channelways and intermineralization fracturing, with rapidly changing physico-chemical conditions during ore deposition, provide some theoretical explanation of the structural and mineralogical features found at Oruro. Not only may they explain the deposition in a near-surface environment of minerals with textures and compositions characteristic of a more intense depth zone, but also may explain the superimposition of minerals and textures with relatively shallow significance (silver sulphosalts, stannite, franckeite, etc.) on an earlier mineral aggregate of deeper significance (quartz-pyrite-cassiterite).

Under the new physico-chemical conditions following vein reopening, cassiterite (SnO_2) and pyrite (FeS_2) apparently were not stable, whereas stannite (Cu_2FeSnS_4) was stable. Somewhat later, as the solutions cooled, or perhaps as a gas phase developed, franckeite ($Pb_5Sn_3Sb_2S_{14}$) became the stable tin-bearing mineral. With the changed stability conditions, other minerals were affected similarly, so a variety of silver-bearing sulphosalts were deposited instead of the relatively simple minerals of the first stage.

The probable change in nature of the solutions from liquid to gas and from alkaline to acid was expressed by the character of the wall-rock alteration and gangue minerals. Sericite, pyrite, and quartz gave way to alunite, dickite and kaolinite in the wall rocks. Finally, the later group, with marcasite, formed in the veins.

Genetic Classification.—The Oruro tin-silver veins clearly belong to the large group of hypogene ore deposits that formed under favorable physico-chemical conditions from circulating hydrothermal solutions of magmatic deri-

[106] Ross, C. S., Differentiation as a source of vein and ore-forming materials: Ore deposits of the Western States (Lindgren volume), pp. 128–144, Am. Inst. Min. Met. Eng., New York, 1933. See particularly pages 133, 134, and 143.

Graton, L. C., Nature of the ore-forming fluid: ECON. GEOL., vol. 35, Supplement no. 2, March–April 1940.

vation. Although disconcerting gaps exist in our detailed knowledge of certain important aspects of the general geologic environment, the temperature-pressure-composition relations, discussed in the preceding pages, provide sufficient data for the classification of the Oruro veins in Lindgren's genetic grouping of the hydrothermal ore deposits.[107]

The factors temperature and pressure, the latter as a function of depth, are used by Lindgren in defining his "depth zones." If depth alone were diagnostic, the Oruro veins would be epithermal, but the inferred temperature range and possible pressure conditions make this unlikely. Moreover, the superimposition of the silver-sulphosalt stage minerals on the early quartz-pyrite-cassiterite minerals, following a structural break, resulted in complex veins with mineral assemblages characteristic of more than one depth zone, and suggests that telescoping took place during ore deposition.

Telescoped ore deposits have a natural home in the "xenothermal" class proposed by Buddington.[108] As defined, this term includes those veins that formed at or below a depth of 2,000 to 3,000 feet, and at a temperature of 300-500° C. The Oruro ore deposit, like those at Llallagua and Carguaicollo,[109] fits admirably into this group and, from the point of view of physico-chemical intensity, stands somewhere between these two.

[107] Lindgren, W., Mineral Deposits, Chapter XXVI, McGraw-Hill Book Co., New York, 1933.

[108] Buddington, A. F., High temperature mineral associations at shallow to moderate depths: Econ. Geol., vol. 30, pp. 205–222, 1935.

[109] Turneaure, F. S. and Gibson, Russell, Tin deposits of Carguaicollo, Bolivia: Am. Jour. Sci., vol. 243-A, The Daly Volume, pp. 523–541, 1945.

ORE AND GRANITIZATION.

C. J. SULLIVAN.

CONTENTS.

PAGE
Abstract 471
Introduction 472
Primary differentiation, "volcanic" activity, granitization 473
Original separation of elements 473
Effect of "volcanic" activity 473
Return to chemical equilibrium 474
Relation of preceding "volcanic" activity to variation of nature of granitic rocks with geological time 474
Relationship of preceding "volcanic" activity to metallogenetic epochs and metalliferous provinces 475
Distribution of ore in geological time 475
Lithophile elements 475
Chalcophile and siderophile elements 475
Summary of ore distribution in geological time 481
Further applications of hypothesis 482
Association of particular ores with specific rocks 483
Acid granite and the tin assemblage 484
Vanadium and chromium 485
Copper, silver, gold 485
Lead, zinc, tungsten 486
Quartz-poor rocks 486
Crystal settling 487
Norite and nickel 487
Spectroscopic prospecting 488
Relationship between certain types of batholiths, contact-metasomatism and ore deposition 488
Characters of synchronous batholiths 488
Characters of subsequent batholiths 489
Relationship to ore deposition 489
Mount Painter, South Australia 491
Brocks Creek, Northern Territory 491
Broken Hill, N. S. W. 492
General application 493
Genetic classification of ore deposits 493
Conclusions 495
Acknowledgments 496
Bibliography 496

ABSTRACT.

The process of granitization may be regarded as an approximate re-establishment of the geochemical equilibrium attained when the earth first cooled, but which was later upset by the large quantities of predominantly

basic volcanic rocks brought into the sial by physical, as distinct from chemical, forces.

On the basis of the granitization hypothesis, an attempt is made to explain the variation in composition of granitic rocks and of associated ore deposits during geological time by relating them to preceding volcanic activity. This leads to a possible explanation of the origin of some metalliferous provinces—*e.g.*, the Western Australian gold province.

Evidence is offered in support of the hypothesis that, in the process of the formation of a granitic rock, the valuable elements of ore deposits are concentrated in inverse ratio to the extent to which they are incorporated by isomorphous substitution in the common rock-forming minerals. This is held to explain, to a large extent, the association of specific ores with specific types of granitic rocks.

Attention is drawn to the economic importance of distinguishing between synchronous and subsequent batholiths and suggestions are made for prospecting in areas in which synchronous batholiths occur.

It is considered important to distinguish between ore deposits formed during a period of granitization and those of "volcanic"—or abyssal—origin: *e.g.*, in the former case, given favorable conditions, some sort of zonal arrangement of the mineralization is to be expected; in the latter case, fluctuations in the depth of geoisotherms might easily cause ores, theoretically belonging to various depth-zones, to occur at the same vertical horizon.

INTRODUCTION.

In recent years Locke (47),[1] Dunn (21), Backlund (3), Shand (61), Rastall (54, 55), Reynolds (57, 58, 59) Read (56) and others have discussed evidence indicating the derivation of granite and allied rocks by the granitization of sediments and other crustal material, and this concept has now been accepted by many investigators. Much of the theory of ore deposition in the past has been based on differentiation, which has been accepted as the dominant factor in the development of granitic rocks, but, as Elie de Beaumont (20 (a)), dealing with the origin of granite, remarked 100 years ago, "this question is, even today, somewhat obscure." It seems to the author that in accepting, until recently, the basic importance of differentiation processes in the formation of granites, some fruitful lines of investigation into the origin of ore deposits have been overlooked.

For the past twelve years, the writer has been engaged mainly in the field study of Australian ore deposits; and certain broad problems of the relationship of ore deposits to rock types have become apparent.

There may be no simple explanation to many of the problems, but it is here proposed that the answer to some of them may be found if it is assumed that:

(a) Granitic rocks and their associated ore deposits are formed mainly from sediments and other rocks available in the sial at the time granitization takes place.

(b) "Volcanic" rocks in the sense of Read (56)—including basalt, dolerite, gabbro and, probably, their acid differentiates—originate from below the sial. The ores associated with these rocks also have an abyssal origin. The "volcanic" rocks and associated ore represent an addition to the primordial crustal material.

[1] The numbers in parentheses refer to bibliography at end of the paper.

PRIMARY DIFFERENTIATION, "VOLCANIC" ACTIVITY, GRANITIZATION.

Original Separation of Elements.—Goldschmidt (34) considered that when the earth first cooled, the elements, including the metals, distributed themselves in accordance with geochemical laws, the lithophile elements tending to remain in the outer crust, the chalcophile and siderophile elements tending to be depressed to deeper levels. Goldschmidt's classification of elements according to their lithophile, chalcophile or siderophile properties is shown in Table 1.

TABLE 1.

GOLDSCHMIDT'S CLASSIFICATION OF THE ELEMENTS.

Iron siderophile	Sulphide chalcophile	Silicate lithophile
Fe, Ni, Co	((O)), S, Se, Te	O, (S), (P), (H)
P, (As), C	Fe, Cr, (Ni), (Co)	Si, Ti, Zr, Hf, Th
Ru, Rh, Pd	Cu, Zn, Cd, Pb	(Sn)
Os, Ir, Pt, Au*	Sn, Ge, Mo	F, Cl, Br, I
Ge,* Sn*	As, Sb, Bi	B, Al, (Ga), Sc, Y
Mo, (W)	Ag, (Au), Hg	La, Ce, Pr, Nd, Sm
(Nb), Ta	Pd, Ru, (Pt)	Eu, Gd, Tb, Dy
(Se), (Te)	Ga, In, Tl	Ho, Er, Tu, Yb, Cp
	(Cr)	Li, Na, K, Rb, Cs
		Be, Mg, Ca, Sr, Ba
		(Fe), V, Cr, Mn
		((Ni)), ((Co)), Nb, Ta
		W, U, ((C))

* That germanium, tin, and gold are distinctly siderophile elements has recently been proved by independent studies on meteorites and on metallurgical products.

The separation of the elements outlined by Goldschmidt depends broadly on the position of the elements in the electromotive series. Those elements high in the series have been able to displace iron from the ionic melt which has crystallized as the lithosphere and hence they are preferentially segregated therein. The elements low in the electromotive series have been displaced by iron from the ionic liquid and are thus siderophile. The chalcophile elements are those which form homopolar compounds with the metalloids and cannot coexist in an ionic environment with appreciable concentrations of the metalloid ions. They comprise, for the most part, the metals of the sulphide group of analytical chemistry (1).

Effect of "Volcanic" Activity.—The separation of the elements outlined above probably took place while the earth-material was still in a largely fluid state. Throughout geological time, physical as distinct from chemical forces have resulted in the bringing into the sial of large quantities of "volcanic" rocks, predominantly basic in character, together with associated chalcophile and siderophile metallic elements. This process must have upset the geochemical equilibrium established at the first cooling of the earth.

It appears, then, that while the earth was largely fluid, geochemical equilibrium required that an acid silicate crust be formed, and, therefore, that the upward movement of basic rocks must have caused some degree of chemical instability in the crust.

Return to Chemical Equilibrium.—If it is supposed that layers of basalt, for example, are intercalated with layers of typical sialic material and depressed deeply into the crust, it might be expected that, with the return of temperature conditions towards those holding when the earth first cooled, the geochemical laws of element distribution would tend to re-assert themselves. The result would be the formation of a granitic layer in the outer crust as in the case of the first earth-cooling.

RELATION OF PRECEDING "VOLCANIC" ACTIVITY TO VARIATION OF NATURE OF GRANITIC ROCKS WITH GEOLOGICAL TIME.

As geological time has progressed, there has been a gradual increase in the average basicity of granitic rocks. Thus Daly (18 (a)) shows that the average Precambrian granite contains some 1.3 percent more silica and less lime and magnesia than the average post-Cambrian granite. The relevant sections of Daly's table are given in Table 2.

TABLE 2.

ANALYSES OF GRANITIC ROCKS OF PRECAMBRIAN AND POST-CAMBRIAN AGES.
(Average compositions)

	Precambrian granite	Post-Cambrian granite
Number of analyses.....	47	184
SiO_2	71.06	69.73
TiO_2	0.48	0.34
Al_2O_3	14.10	14.98
Fe_2O_3	1.46	1.62
FeO	1.63	1.66
MnO	0.18	0.11
MgO	0.59	1.08
CaO	1.97[a]	2.20[b]
Na_2O	3.24	3.28
K_2O	4.50	3.95
H_2O	0.69	0.78
P_2O_5	0.10	0.27

[a] Includes 0.08 percent BaO and 0.01 percent SrO.
[b] Includes 0.06 percent BaO and 0.02 percent SrO.

Daly (18 (d)) also points out that more than nine-tenths of the world's granite belongs to Precambrian terrains; he notes the special development of granodiorite in post-Cambrian times and this is also true of diorites and monzonites, which Shand (61 (a)) suggests may be due to hybridization. The abundance of granite pegmatites in the Precambrian has been noted by many writers, and most students of the early Precambrian in particular have drawn attention to the relatively high acidity of the intrusives of that age, as compared with that of later granitic rocks.

The above facts can be explained if it is assumed that these rocks have been formed from crustal material which has become increasingly basic by the addition of "volcanic" rocks, predominantly basic in composition.

The scarcity of alkaline, quartz-poor rocks in the Precambrian,[2] referred to by Daly (18 (a)) and Lindgren (45), may be related to the comparative

[2] The nephelinized paragneisses of the Bancroft area, Ontario (35), which are of Precambrian age (Grenville) appear to have been formed by the alteration of calcareous rocks.

scarcity of limestone in the earliest rocks. Twenhofel (71) comments on the scarcity of limestone in the Archean rocks which is a natural corollary of the non-existence in the earliest times of lime-secreting animals and plants. There seems to be a good deal of evidence that the alkaline rocks result from the granitization or assimilation of limestone (61 (b)).

RELATIONSHIP OF PRECEDING "VOLCANIC" ACTIVITY TO METALLOGENETIC EPOCHS AND METALLIFEROUS PROVINCES.

Distribution of Ore in Geological Time.

Niggli (52 (a)) noted the variation of ore deposits with geological time and he and other European geologists speak of "young" and "old" deposits. He ascribed the differences noted to the effects of erosion, implying that deep-seated deposits were found in old terrains. Bateman (6 (a)) doubts the erosion hypothesis as an explanation of metalliferous provinces and epochs and suggests the possibility of atomic fission for an alternative suggestion.

It is contended here that in the deposits genetically related to granitic rocks, lithophile ore elements are found in the earlier geological periods, while chalcophile and siderophile elements, irrespective of their temperatures of deposition and, presumably, of their depths of deposition, become more prominent in the later periods of geological time. This may have resulted from the gradual enrichment of the crust in the endogenetic elements, mainly by "volcanic" activity, thus making them available for emplacement during granitization.

Lithophile Elements.—Important lithophile elements (Table 1) are U, Th, Cb, V and Be. The major uranium concentrations are in the early Precambrian pegmatites and the two most important known hydrothermal uranium deposits (Shinkolobwe and Great Bear Lake) are Precambrian in age, though the occurrence at Great Bear Lake has a low temperature of deposition (42). The thorium deposits of Travancore, Brazil, and Western Australia are related to Precambrian granites, but those of the east coast of Australia are derived from granites which are Devonian to Permian in age.

Tantalum, niobium (4) and beryllium (63) are produced mainly from the pegmatites of ancient terrains of Northwestern Australia, Brazil, India, Canada, South Africa and the United States. It is a striking fact that later granites have not concentrated important quantities of these elements.

The element vanadium, as explained later, is a special case and has rarely been concentrated into payable deposits.

The lithophile elements are not found associated with "volcanic" activity; the addition of basic magma to the crust merely dilutes the concentrations of these elements available for emplacement during granitization. Thus, Holmes (39) indicates that the average sialic material contains about 150 times as much uranium, for example, as the average earth material.

Chalcophile and Siderophile Elements.—Copper is typical of the chalcophile elements and the crust has been progressively enriched in it by the addition of

basalts, which analyses (12) and common observation show to be relatively rich in this element.

Of a world-production in 1945 of approximately two and a half million tons, over 700,000 tons came from the United States (mainly from the late Mesozoic and early Tertiary deposits of the Southwestern States);[3] Chile (late Mesozoic to Tertiary) 470,000 tons; Japan (Tertiary) 95,000 tons; Yugoslavia (Tertiary) 64,000 tons; Mexico (Tertiary) 61,000 tons; Peru (Tertiary) 29,000 tons. These deposits have been formed at relatively high temperatures and thus belie the erosion theory.

Less important production has come from the Paleozoic areas of Australia (24,000 tons); Burma (12,000 tons, 1943); Spain (8,000 tons, 1940); Germany and Austria (23,000 tons, 1944).

Some 250,000 tons were obtained from the late Precambrian to early Paleozoic deposits of the Belgian Congo and Rhodesia, which are definitely related to granitization (19). Canada produced 216,000 tons; over half of this production, however, came from the Sudbury deposits, which are genetically related to norites and other basic rocks of "volcanic" (sub-sialic) origin; at Noranda, Quebec, the second most important producer, the latest intrusive is gabbro (49).

Copper ores related to early Precambrian granites are of very minor importance. The whole of Western Australia, whose metallization is exclusively Precambrian, is conspicuously poor in copper. The most important source has been the Whim Creek district (27), which has produced only 10,000 tons of metal. The deposits are genetically related to Nullagine (late Precambrian) volcanic activity, and one of them appears to have been formed close to an old crater. The Nullagine volcanic activity gave rise to minor base metal deposits elsewhere, but the main period of metallization in Western Australia is related to granitic rocks of Mosquito Creek (middle Precambrian) age, and no important copper deposits of this age have been discovered.

Tin is normally deposited at high temperature and at considerable depth, and if the erosion hypothesis were sound, its occurrence in the old formations would be expected. When it is considered that tin is normally associated with acid granite and that Daly (18 (a)) has estimated that nine-tenths of the acid granites occur in the Precambrian, this probability would seem to be increased.

However, the world's tin production has come from the Burma-Malay-N.E.I. province (Mesozoic); Bolivia (Post-Mesozoic); Cornwall, Saxony and Bohemia, Eastern Australia (late Paleozoic); Nigeria and the Belgian Congo (probably late Precambrian). The early Precambrian terrains are conspicuously poor in tin, despite their high proportion of acid granites.

The contrast in time distribution between the siderophile element tin and the related, but lithophile elements, tantalum and columbium, is very marked.

The explanation may lie in the fact that, as shown by Goldschmidt (34). tin is predominantly a siderophile element, and it appears likely that, as a

[3] The late Precambrian Michigan amygdaloids are not taken into account, as the ore appears to be of abyssal origin.

result of the partition of elements which took place when the earth material was still largely liquid, the lithosphere was impoverished in tin.

The appearance of tin deposits in the later periods of geological time is considered to be related to the fact that tin may be brought into the lithosphere by volcanic rocks. This is shown by the occurrence of tin-rich rhyolite in Mexico, Nevada and New Mexico (46 (a)) and by the close genetic relationship between volcanic rocks and the important Bolivian tin deposits of Potosi (24) Oruro (16) and Llalagua (32), for example.

It is not concluded from this that tin may be introduced into the crust by acid volcanic rocks only, and, as explained in the next section of this paper, the occurrence of cassiterite crystals in rhyolite, and the association of tin deposits with acid volcanic rocks, does not necessarily mean that these rocks contain more tin than do more basic varieties. These phenomena do indicate, however, that tin may be introduced into the crust by volcanic rocks.

It may be noted that the column of rocks intruded by the Juarassic to Cretaceous granite of Malaya includes the considerable thickness of the predominantly acid Pahang volcanics of late Paleozoic age (60). The Permian granites of Eastern Australia, whose formation was accompanied by considerable tin metallization, were preceded during the Ordovician, Silurian, Devonian and Carboniferous by tuffs and other predominantly acid volcanic rocks (13). Very little copper was concentrated during the formation of the Permian granite.

It is concluded that acid granites will give rise to tin deposits only when tin is available within the sialic material from which the granite is formed. This is a possible answer to the question posed by Rastall (55), who contrasts the Hercynian granites which introduced the rich tin deposits of Cornwall, Brittany, the Erzgebirge, Spain and Portugal with the older Caledonian granite which did not introduce tin, though in many ways the granites are similar and both are acid types. Once a metal has been introduced into the crust by "volcanic" activity, it may be preserved and concentrated in sediments and may re-appear in several cycles of metallization.

Analogous arguments may be used to explain to some extent the occurrence in geological time of such elements as tungsten, which is distributed around the Pacific volcanic belt (44); of gold and silver, which may be brought into the crust with certain types of volcanic rocks; and of lead and zinc, which were introduced into the post-orogenic, post-granite Nullagine series at Braeside, Western Australia (28) during a cycle of volcanic activity which gave rise to flows of acid and basic rocks.

Lead and zinc of the Braeside occurrence are interesting for the reasons given above. The rocks in which the lead-zinc-bearing quartz veins occur are relatively unaltered acid and basic lavas, interbedded with typical sediments of Nullagine (late Precambrian) age. In Northwestern Australia and in the Northern Territory, these beds have been only gently folded (dips, 8 to 15 degrees) and in places they rest unconformably on granite of Mosquito Creek (middle Precambrian) age, with which the main metallization (gold) of Western Australia and the Northern Territory is generally

considered to be connected. It seems clear that the lead and zinc at Braeside are of abyssal origin and are not related to granitization.

A consideration of the literature leads to the conclusion that a considerable number of important lead-zinc deposits may more logically be related to "volcanic" activity than to granite, and, on the present hypothesis, it would be concluded that they originated below the sial. Among the deposts which are closely associated with "volcanic" rocks are those at Trepeca, Yugoslavia; Bawdwin, Burma (6 (b)); Buchans, Newfoundland (51); Captain's Flat, N.S.W. (41), and Read-Rosebery, Tasmania (29). It has been the custom to ascribe the origin of most ore deposits to granite, whether the latter has actually been observed in the vicinity of the deposit or not, but the Braeside case shows that "volcanic" activity, when prior differentiation has occurred, may enrich the crust in lead and zinc, which would then be available for emplacement during later cycles of granitization. There is no doubt, of course, that many deposits including the Broken Hill (N.S.W.) lode, are closely associated with granite.

The lead of some "telemagmatic" or "telethermal" deposits may also be of sub-sialic origin; these usually cannot be directly related to the formation of granite. Thus, at Narlarla, Kimberley Division, Western Australia (30), a lead deposit occurs in Devonian limestone, which certainly post-dates the latest granitic activity by a number of geological periods.

Again, as emphasized by Holmes (39), there has been a continuous addition of lead to the crust by the disintegration of uranium and thorium, which are much more abundant in the sial than in the average earth material. At present, the addition of basalt to the crust would dilute the crust's lead content. Thus, Hevesy and Hobbie (38) found that granitic rocks have about five times the lead content of gabbro or basalt, though ultrabasic rocks contain two or three times as much as basalt.

It would thus seem that the amount of lead available in the crust has been influenced by a number of factors, but, on the whole, it must have increased as geological time has progressed. Of a world lead production in 1945 of approximately 1,700,000 tons, over 600,000 tons came from the predominantly post-Paleozoic deposits of the United States and Mexico, some 150,000 tons were obtained from Germany and Austria (mainly Triassic) and a large proportion of the remainder came from other Mesozoic and Paleozoic deposits. Production from the Precambrian was largely accounted for by two isolated deposits, viz. Broken Hill,[4] N.S.W. (153,000 tons), and the Sullivan Mine, B.C. (163,000 tons). To the end of 1944, the Western Australian Precambrian shield, which occupies a very large area, had produced only 66,000 tons of lead.

Gold is remarkably concentrated in the Western Australian deposits within areas occupied by greenstones. Thus, it is estimated that of the 51,500,000 ounces of gold produced from this metalliferous province from 1886 to 1947, over 90 percent came from the greenstones (mainly chloritized, basic to inter-

[4] Recent unpublished information throws considerable doubt on the Archean age of the Broken Hill granite. It appears likely that the granite may be of late Precambrian or early Paleozoic age.

mediate lavas and dolerites) though these probably do not occupy a greater area [5] than the sedimentary rocks of Mosquito Creek and similar age, which, along with the greenstones, were intruded by granite towards the close of the Mosquito Creek epoch (22). Are the greenstones to be understood as source rocks for gold in the same sense that marine organic shales have been regarded as source beds for petroleum? It has often been assumed that the greenstones are "favorable" for the occurrence of gold because of physical and chemical properties which enable them to localize gold deposits, but it is generally difficult to determine just how these factors have had such a favorable effect.

R. T. Prider, who has made a special study of the Western Australian greenstones, considers (personal communication) that both the volcanic rocks and the dolerites which intrude them are related to tholeiitic magmas, implying that the magmas from which the greenstones were formed underwent considerable differentiation before intrusion. These rocks are, therefore, not simple basalts and it is possible that, during the process of differentiation, they were enriched in gold.

Apart from the very widespread association of Western Australian gold deposits with greenstones, one of the most notable features is the persistent occurrence of ore close to albite-porphyry dikes. This association is not confined to Western Australia, and, as noted by Gallagher (33), is of world-wide occurrence.

One of the most interesting examples is on the "Golden Mile," Kalgoorlie [6] (68 (a), 36 (a)), where there is a close association of albite-porphyry dikes with gold-bearing lodes. The dikes occur in fine- and medium-grained chloritized, basic igneous rocks intercalated with slates.

The emplacement of the porphyries and the formation of the lodes appear to be closely related in time; some of the dikes have been guided by the same fracture-pattern which localized the ore bodies (31 (a)). Other dikes are confined to slate belts.

One occurrence known as the Boulder Dyke has been described (68 (b)) as "a composite belt of slate and porphyry" and as a "lit par lit intrusion" (31 (b)). The present writer recently had an opportunity to inspect this "dike" in the Lake View and Star Mine. Where examined, it consisted of alternating narrow bands of graphitic slate and albite-porphyry, the slates having every appearance of being of sedimentary origin and (in the exposures inspected) showing little sign of distortion by the porphyry. Stillwell (68 (c)) has discussed this occurrence fully and he was at a loss to account for the relatively undisturbed sedimentary rocks in the midst of igneous rocks; he was inclined to call the slate sheared igneous rocks, impregnated with graphite. In the writer's opinion, however, the evidence does not support this conclusion, and it is far more likely that the slates are true sediments as Gustafson and Miller (36 (b)) concluded.

[5] The older maps of Western Australia are misleading. For a revision of the geology of a given area and as an example of the selective occurrence of gold deposits in the greenstones see reference 22.

[6] To the end of 1947, the field had produced approximately 27,000,000 fine ounces of gold.

In the North Kalgoorlie Mine, the author recently inspected an occurrence of what is locally known as "jasper," situated at the contact between quartz-dolerite-greenstone and the underlying carbonated pillow-lavas. The "jasper" has obviously been a thinly-bedded sediment which is now highly silicified and, in addition, contains much albite. It may most accurately be described as an adinole. This rock is closely associated with a large gold-bearing deposit and itself contains up to 2 dwt gold per ton. The rock is very comparable with portions of the "Boulder Dyke."

Stillwell (68 (a)) found numerous chloritized rock fragments, as well as pseudomorphs after hornblende, in the albite-rich dikes in the greenstones; these are possible evidence of replacement.

In an interesting article, Reynolds (58) gives a review of a description by Bowen of the formation of soda-rich aplite dikes by the alteration of slates and also an account of a description by Van Bemmelen of soda-rich aplitic veins in the upper portions of a granitic mass in contact with andesite. Van Bemmelen believed that the veins may have been produced by granitization. Gummer and Burr (35) have recently described the development of albitite dikes from altered sediments.

A detailed description has been given by Bastin (5) of the formation by "hydrothermal" processes of albite-rich "aplite dikes" in the Nipissing diabase. His study showed conclusively that the dikes formed by a process of replacement, not by intrusion from a melt. These dikes usually have a maximum width of 2 feet and their length "rarely exceeds a few hundred feet." The dikes at Kalgoorlie vary in width from 1 foot to 100 feet; the "Boulder Dyke" of slate and porphyry is, in places, over 300 feet wide. There seems no good reason to suppose, however, that the occurrences described by Bastin cannot be formed on a larger scale.

Bastin shows that the formation of the albite-rich rock is closely connected with the introduction of iron and copper sulphides and, in fact, that there is "no recorded break" between the formation and the dike and the metallization.

Backlund (3) considers that the conversion of the normal geosynclinal pile into granite-like rocks involves the addition of soda and silica. Can these albite-rich dikes be regarded as marking the upper limits reached by a wave of granitization, which has driven ahead of it gold and other elements largely derived from the greenstones which have been converted to granitic rock? Admittedly, this conception is somewhat hypothetical, but normal differentiation and intrusion do not seem to explain the facts at Kalgoorlie and in the Western Australian gold province in general. It is evident that fundamental knowledge of rock and ore genesis is still lacking.[7]

Goldschmidt (34) has shown that some meteorites are 1,000 times richer in gold than is the average sialic material. Furthermore, the siderophile nature of gold has also been proved by the study of metallurgical products, and is, in fact, to be expected from the low position of the noble metals generally

[7] Shand (61. p. 162) aptly remarks: "It must now be abundantly clear that the variation of mineralogical and chemical composition within bodies of eruptive rock are due to many causes, some of which we know, and others we can only guess at. Certainly there is no single process of 'magmatic differentiation' and the sooner that pretentious and misleading term is dropped, the better for petrology."

in the electromotive series. It is thus reasonable to suppose that the early crust had a relatively low gold content. The association of some gold provinces, *e.g.*, the Pacific province, with volcanic activity suggests a method whereby the metal may have been returned to the sial.

However, in spite of the fact that gold is a siderophile element, the Precambrian areas are outstanding producers—*e.g.*, of a world production in 1939 of approximately 40,000,000 ounces, outstanding contributions were made by the following Precambrian provinces: Africa, 15,500,000 ounces; Canada, 5,100,000 ounces; and Western Australia, 1,188,000 ounces.[8] These predominantly Precambrian areas thus accounted for over 50 percent of the world's production in 1939. Nevertheless, younger areas also contain very important gold-provinces; *e.g.*, the United States and Alaska produced 4,600,000 ounces; the Philippine Islands, 1,040,000 ounces; New Guinea, Fiji and New Zealand, 500,000 ounces; and South America, 1,800,000 ounces.

It is pointed out that the Precambrian represents about 75 percent of geological time and that the granites of early Precambrian time have not introduced important quantities of gold. Thus Moore (50) shows that, in Canada, the earliest (Laurentian) granite gave rise to only minor gold deposits, whereas numerous deposits are related to the later Algoman and Keeweenawan granites. Considerable volcanic activity occurred after the formation of the Laurentian granite and before the emplacement of the Algoman and Keeweenawan granites. Similarly, in Western Australia and in the Northern Territory, the Archean granite and gneiss gave rise to very few important deposits of gold or other chalcophile or siderophile elements. Most geologists relate the gold deposits to the Mosquito Creek (younger) granite. The South African deposits occur in the late Precambrian Witwatersrand System. Lavas were extruded during the immense interval of time represented by the Pengola and Swaziland Systems. The important deposits of Siberia are related to late Precambrian and Paleozoic granite and granodiorite (23).

Summary of Ore Distribution in Geological Time.—It is realized that, in the above attempt to correlate and explain the distribution of ore in relation to age, one could only hope to show general trends. No reference has been made to the relative areas occupied by the rocks of various ages, though it is believed that, for the time units chosen, these areas are comparable. Current production figures are not always a guide to the degree of metallization, as, to some extent, they are a function of the time during which mining has taken place.

In spite of these imperfections in the argument, it is considered that the evidence presented shows that there is but little correlation between the temperature of formation of ore deposits and their distribution in geological time and, hence, that Niggli's explanation (52 (a)) on the basis of the depth of erosion is probably untenable. Broadly, the lithophile elements are found in genetic relationship to the earliest granitic rocks, and the chalcophile and siderophile elements, irrespective of their temperatures of deposition, are found in the later periods of geological time.

[8] Some 5,200,000 ounces are estimated to have been produced from the U. S. S. R., a considerable proportion of which probably came from the late Precambrian Siberian province.

Further Applications of Hypothesis.

In order to illustrate the application of the ideas outlined above, some examples may be considered.

Niggli (52 (b)) postulated that certain processes of differentiation constantly gave rise to certain ore deposits and that, in particular, the differentiation processes leading to the formation of the calc-alkali clan was fruitful of ore deposits. However, the calc-alkali clan is also called the Pacific clan and the formation of these rocks has usually been preceded by outpourings of volcanic rocks. It is considered that this partly explains the richness and variety of ore deposits which are associated with them.

This difference of approach may be illustrated in connection with Lindgren's (45) classic essay on differentiation and ore deposition in the Cordilleran Region of the Western United States. Lindgren notes the acid types of intrusives and the "simple" and localized ore deposits occurring in the Precambrian and contrasts these with the intermediate types of intrusives and the large and varied ore deposits which were formed in the Mesozoic and later periods. He ascribes these differences to the effects of differentiation, and states that the cycle of differentiation culminated in the production of alkaline rocks.

It is pointed out here that the Precambrian intrusives mentioned were formed towards the close of that era when 75 percent of geological time had elapsed; it is difficult to believe that this time was insufficient for the processes of differentiation to take effect, and for varied ore deposits to be formed. The alkaline rocks may have resulted from the assimilation of limestone.

The explanation of the phenomena described by Lindgren may lie in the fact that, during the Paleozoic, repeated "volcanic" activity took place and that the Cordilleran geosynclines were thereby enriched in basic rocks and in associated chalcophile metallic elements. During subsequent folding, granitization produced plutonic rocks of intermediate type with numerous associated ore deposits.

Repeated localization of the one type of mineral in a particular province during successive periods of metallization—*e.g.*, the repeated copper metallization in Arizona—can be explained if it is assumed that, once an element is introduced into the crust, it remains there during successive cycles of erosion and sedimentation. Under these circumstances, it would not be necessary to assume the existence of an unusually copper-rich magma at depth. Thus Dunn (21) has remarked that

> ore minerals deposited in the early crusts may become part of the magma formed from any part of the crust or may be removed to a higher zone by solutions. . . . The initial distribution of metals in various parts of the primordial crust has presumably been largely responsible for the present-day distribution of metallogenetic provinces in various parts of the world, in rocks of later age.

Ore provinces are often co-extensive with geosynclines because a series of intrusives with associated ore deposits occurring in the same geosyncline are formed from essentially similar materials.

Organic matter sometimes plays a part in the localization of ore provinces; *e.g.,* uranium is commonly precipitated by carbonaceous material, as in Colorado, Utah and Sweden. The fact that in Canada and in Russia uranium has been found in pegmatites associated with carbonaceous material called thucholite (53 (a)), is suggestive of the way in which this association might persist after the granitization of carbonaceous sediments carrying uranium. Similarly, the most important occurrences of vanadium are associated with hydrocarbons.

ASSOCIATION OF PARTICULAR ORES WITH SPECIFIC ROCKS.

In the preceding section, a possible explanation has been advanced for the fact that some granitic rocks have given rise to ore deposits, whereas others, of very similar type, have not done so. It is postulated that, in the case of the barren granites, the ore elements were not available in the rocks from which these particular granites were formed.[9]

However, in examining the relationship between the origin of granitic rocks and the origin of ore deposits, it is very necessary to consider the close and world-wide association that does exist between specific types of ore deposits and specific types of igneous rocks (*e.g.,* between tin deposits and acid granites), and to consider possible processes whereby metallic elements, which, if they were evenly distributed throughout the silicate crust, would amount to very small percentages indeed, have been concentrated into workable deposits.

These phenomena have been discussed by Niggli (52 (c)), Buddington (15), Lindgren (46) and Bateman (6 (c)), who have stated or implied that the associations are confirmatory evidence of the "magmatic" origin of both granitic rock and the associated ores; it is usually suggested that the associations result from "magmatic differentiation." Thus Bateman states:

> Field observations disclose an association of certain minerals with specific rocks that is so general and widespread as to preclude coincidence. This association establishes a definite relationship between the minerals and rocks, indicating thereby a magmatic source for both. For example, primary platinum deposits occur only in ultrabasic rocks, such as dunite or peridotite; diamonds in kimberlite; chromite in peridotite or serpentine; ilmenite in gabbro or anorthosite; titaniferous magnetite in gabbro or anorthosite; corundum in quartz-free rocks, such as nepheline syenite; nickeliferous sulphides in norite or gabbro; tin in silicic granites; and beryl in granite pegmatite. These associations are so universal as to render inescapable the conclusion that the rock and associated ore sprang from the same magma.

The diagram published by both Bateman (6 (c)) and Buddington (15 (a)) indicates clearly that they considered the association of specific ores with specific rock types to be a function of magmatic differentiation.

It is postulated here, however, that the observed genetic relationships between particular granitic rocks and particular types of ore deposits depend chiefly on the degree to which the particular rock, during its formation, is able to concentrate the metallic elements which were originally dispersed through

[9] This explanation was partly implied by Dunn's remarks (21), already quoted, though Dunn did not refer to the effects of "volcanic" activity, which are emphasized in this paper.

the rocks from which the granite was formed. The amount of water and other volatile substances present in the original rocks may have a bearing on the efficiency of concentration, but it is considered that the ability of a particular plutonic rock to concentrate a particular element depends primarily on the lattice structures [10] of the crystals forming the plutonic rock, on the ionic radii [11] and valency of the elements constituting the crystals forming the plutonic rock and on the ionic radii and valency of the elements to be concentrated.

The principles of isomorphous substitution have been discussed by Goldschmidt (34), Bragg (10) and others. Basically, these are:

(a) Elements with similar ionic radii tend to replace each other in crystal lattices.
(b) Elements of high ionic charge (valency) tend to replace those of lower ionic charge.
(c) A greater degree of substitution is possible at high temperatures than at lower temperatures.

Acid Granite and the Tin Assemblage.—A good example of the operation of these principles is the well-known association between acid granites and the elements W,[12] Ta, Nb, Bi, Mo and Sn. The ionic radii and valencies of these elements are:

W^{6+}, 0.67; Ta^{5+}, 0.68; Nb^{5+}, 0.70;
Bi^{5+}, 0.74; Mo^{4+}, 0.67; Sn^{4+}, 0.73.

It will be seen that these elements have comparable ionic radii and have high ionic charges. The latter gives them a marked tendency to force their way into crystal lattices, but they can do so only if that lattice contains ions of a size comparable to their own.

An acid granite composed largely of the felspars (which contain the anions Na^{1+}, 0.98; K^{1+}, 1.33; Ca^{2+}, 1.01, and Al^{3+}, 0.57) and of quartz (silicon is a very small anion with a high charge—Si^{4+}, 0.41) is peculiarly fitted to concentrate the above-mentioned elements because these crystals will not absorb them. In the presence of abundant ferro-magnesian minerals, the large-scale concentration of these elements may be practically impossible because of the similar ionic radii of iron (Fe^{2+}, 0.79) and magnesium (Mg^{2+}, 0.75) to those of the elements under discussion, and because of the relatively low valency of iron and magnesium. Accurate analyses of large numbers of common ferro-magnesian minerals are not available to the author at the present time, but analyses quoted in the latest edition of Dana (53 (b)) indicate the degree to which tin, tantalum and columbium can substitute for magnesium and titanium (Ti^{4+}, 0.65). Thus six samples of the magnesium-iron-aluminum-oxide mineral spinel were found to contain 2.96, 0.92, 0.77, 2.0, 0.28 and 0.96 percent SnO_2 respectively. The spinels are most common in basic and ultrabasic

[10] Minerals with high packing index (25) are unfavorable for interstitial solid solution, which may occur in non-stoichiometric minerals. Small atoms, *e.g.*, carbon (I. R. 0.18), may occur in interstitial solid solution.

[11] The ionic radii quoted in this paper are in Angstrom units and are taken mainly from Dana's System of Mineralogy (1944).

[12] Tungsten is frequently concentrated by granodiorite but shows a general relationship to tin. Its valency may be so high that substitution is rendered difficult.

igneous rocks. Various samples of rutile are reported as containing up to 2.67 percent SnO_2, 35.96 percent Ta_2O_5 and 32.15 percent Nb_2O_5 (53 (c)).

Johannsen (40 (a)) reports 0.16 percent SnO_2 in an iron-magnesium mica of the biotite family. Amounts of 0.03 and 0.13 percent Nb_2O_5 have been reported from a nepheline diorite (40 (b)) and 1.22 percent Ta_2O_5 was found in eudyalite from a syenite (40 (c)). In a world-wide study, Ferguson and Bateman (26) found that granites related to tin metallization were abnormally low in magnesia. Stevenson (67) found a high concentration of tin in plagioclase from a granodiorite.

It has generally been believed that tin is associated with a volatile phase of the magma and there has been considerable speculation concerning the role of "pneumatolysis" in the formation of ore deposits generally. The association of tin with the elements B and F, generally present in the minerals tourmaline and topaz, has been taken as evidence of the volatile phase. It is to be noted, however, that B^{3+}, 0.22, is an unusually small ion and that F^{1-}, 1.33 is an unusually large ion; both these types are commonly concentrated along with tin and the other elements enumerated, the reason being that they are not readily accepted into the lattices of the common rock-forming minerals.

Minerals such as samarskite and euxenite are good examples of the influence of ionic radii on the association of elements genetically related to acid granites. For example, the formula for euxenite may be written AB_2O_6 where:

$A = Y^{3+}$, 1.06; Ce^{3+}, 1.18; Ca^{2+}, 1.01; U^{4+}, 1.01; Th^{4+}, 1.06.
$B = Ti^{4+}$, 0.65; Nb^{5+}, 0.70; Ta^{5+}, 0.68; Fe^{3+}, 0.67.

Vanadium and Chromium.—Vanadium (V^{3+}, 0.75; V^{4+}, 0.61; V^{5+}, 0.59) is present in the crust to the extent of 100 grams per ton (34), which is approximately the same as the concentration of copper in the sialic material. However, compared with copper, vanadium-ore deposits are very rare, one of the largest known deposits being that at Minasragra, Peru (6 (d)), which is only 350 feet long and approximately 30 feet wide.

Vanadium is one of the elements which are concentrated only with difficulty, the probable reason being the ease with which it will substitute for ferric iron (Fe^{3+}, 0.67) and for titanium (Ti^{4+}, 0.64). Thus Bray (11) found vanadium in each of 150 samples of igneous rocks; it was most abundant in those rich in ferric iron. Concentrations of vanadium were found in biotite, muscovite (Al^{3+}, 0.57), hornblende and sphene. Chromium occurs similarly to vanadium. Harcourt (37) found biotite from a granite to be rich in vanadium and chromium, and Shimer (62) obtained similar results. Shimer found that the biotites are rich in many minor elements; this mineral would appear to warrant close attention from the spectrographic investigator of the future.

Copper, Silver, Gold.—Copper (Cu^{2+}, 0.98) may be concentrated during the formation of a number of rock species (6 (c)), probably because of its low valency, which lessens its tendency to enter crystal lattices. Gold (Au^{1+}, 1.37) and silver (Ag^{1+}, 1.20) can also be concentrated by a variety of rocks because of their low charge and large ionic size. As previously noted,

however, gold is preferentially concentrated by the soda-rich albite porphyries (33), possibly for the reason that gold may substitute for potassium (K^{1+}, 1.33).

Lead, Zinc, Tungsten.—Lead and zinc have been concentrated into ore deposits to about the same degree. This fact is reflected by production and price statistics. Thus, in 1940, lead production amounted to approximately 1,765,000 tons and zinc production was approximately 1,746,000 tons. Prices for the two metals have generally been comparable, and in 1945 were about 6.5 cents per lb. for lead and 8.25 cents per lb. for zinc.

However, zinc occurs in the crust to the extent of about 40 grams per ton and lead occurs in the proportion of approximately 16 grams per ton (34); thus zinc is about three times more abundant than lead. The zinc ion, Zn^{2+}, 0.79, will substitute for Fe^{2+}, 0.79, and Mg^{2+}, 0.75, while the large lead ion (Pb^{2+}, 1.32) is likely to substitute for potassium (K^{1+}, 1.33) only, of the common rock-forming elements. According to Clarke (17), MgO and FeO together are found in igneous rocks to the extent of about 7.3 percent, as against 3.13 percent for K_2O. Analyses of spinels (53 (d)) indicate all stages of substitution between the ideal formulae $MgAl_2O_4$, $FeAl_2O_4$ and $ZnAl_2O_4$ (gahnite). The investigation of Bray (11) revealed concentrations of zinc in biotite ranging from 0.16 to 0.21 percent, and also showed that zinc had been segregated with the magnetic concentrates. Probably substitution for ferrous iron accounts for Bray's findings. Similarly, tungsten occurs in the crust to the extent of 69 gms per ton and tin to the extent of 40 gms per ton, as compared with lead 16 gms per ton and copper 100 gms per ton (34), but payable concentrations of tungsten and tin are considerably rarer than those of lead or copper. This may be related to the fact that tungsten and tin are difficult to concentrate for the reasons given earlier.

Quartz-poor Rocks.—Niggli (52 (b)) points out that the alkaline or Atlantic-type rocks have not given rise to the occurrence of important ore deposits as compared with rocks of the calc-alkali clan. The same fact is indicated by the Grout-Buddington-Bateman (15 (a)) diagram. Niggli suggests that

> certain processes of orthomagmatic differentiation constantly give rise to certain types of ore deposits . . . in particular, the complete, plutonic, hydrothermal sequence of mineralization is only found in regions of manifold orthomagmatic differentiation of the Pacific type.
>
> How is this connection to be understood? Does it mean that the course of differentiation leading to rock associations of exclusively Atlantic type is in itself unsuitable for the development of residual solutions such as are required for ore deposition, or is it merely an expression of the fact that ore solutions can only penetrate upwards where the earth's crust is subjected to particular tectonic strains? . . . The Atlantic type of rock association seems to be very largely tectonically determined.

May not the answer be, rather, that, in addition to the reasons given in the preceding section of this paper for the relative abundance of ore deposits associated with the Pacific-type rocks, the quartz-poor rocks are inefficient concentrators of the less abundant metallic elements. The quartz crystal has a closely packed lattice, which, together with the small size and high

valency of the silicon ion (Si^{4+}, 0.41), renders solid solution very difficult. Bray (11) found that quartz contained relatively few minor constituents, and Harcourt (37) obtained similar results. Fairbairn (25) has also drawn attention to this fact. Silica also is an important constituent of a large variety of ore deposits and it appears likely that it plays an important part in the transport of the metallic elements from the granitic rock to their point of deposition. Bichan's (8) recent discussion of the possible importance of melts as against "hydrothermal solutions" draws attention to this point. The possibility that metals may be transported in colloidal suspensions in which silica plays an important role may also be mentioned. It is therefore considered that if abundant quartz crystallizes during the formation of a granitic rock, the likelihood of concentration of the rarer elements increases. If, for example, the granitization of a column of rocks which included a tin-rich rhyolite and limestone, gave rise to a nepheline-syenite, the tin of the rhyolite might not be concentrated in ore deposits, partly owing to the absence of quartz.

Crystal Settling.—It is becoming recognized that the metallic content of most ore deposits, even those associated with basic rocks, is derived from the metals available when crystallization is virtually complete. For example, important magnetite deposits associated with granitic rocks are now being found to be late-stage products.

That many of these deposits are post-silicate was pointed out by Laughlin and Behre (43 (a)); Bateman (7) has since shown that many deposits, even those associated with basic (volcanic) rocks, do not show evidence supporting the idea of early crystal settling.

Norite and Nickel.—Similarly, if norite is simply a modification of gabbro through reaction with shales, as held by the authors whose work was reviewed by Shand (61 (c)), what becomes of the classical explanation of the norite-nickel association? There is a close association between nickel and magnesium, their ionic radii being 0.74 and 0.75 respectively, and so nickel will certainly substitute for magnesium in suitable crystal lattices. A possible explanation of the nickel-norite association may be, then, that in the orthorhombic mineral hypersthene $(Fe, Mg)_2 Si_2O_6$, nickel is unable to substitute isomorphously for magnesium to the extent that it does in a monoclinic pyroxene, such as diopside ($CaMgSi_2O_6$), and thus becomes available for emplacement in ore deposits. No claim is made that there is adequate evidence that this does take place, but the hypothesis could be tested spectroscopically. The hypersthene crystal may contain more lattice defects than does diopside; this would facilitate unmixing of the solid solution by diffusion. A second suggestion is that the contamination of a gabbro by shale would involve a fall in temperature; Bray (11), in his investigation of granites and pegmatites, has shown that the crystals of the pegmatites, which were, presumably, formed at lower temperatures than the corresponding crystals in the granites, contain smaller quantities of trace elements than those from the granites. The "unmixing" of solid solutions, which has commonly been observed in minera-graphic studies, also shows the effect of a fall in temperature on the degree of solid solution.

Spectroscopic Prospecting.—The ideas outlined above need to be taken into account in interpreting the results obtained in spectroscopic studies. It has often been assumed that, if a granitic rock contains a high proportion of a given element, that element should be found in ore deposits surrounding the granitic rock. However, this will depend on the extent to which conditions were suitable for the concentration of the element during the formation of the granitic rock.

A second consideration is the extent to which the present knowledge of isomorphous substitution might be used in a search for the rarer elements in previously unsuspected places. It is not difficult to imagine that, if galena were not subject to oxidation, and were not in itself a valuable mineral and therefore treated metallurgically, the prospector would not have suspected the presence of silver. Similar remarks apply to the presence of cadmium in blende. Is it possible that in some potash-rich dikes of the gold provinces there may be enough gold to make a payable deposit (K^{1+}, 1.33; Au^{1+}, 1.37)? Elements in a state of atomic dispersion are not susceptible to detection by panning and the average chemical analysis does not allow for the possible presence of "foreign" elements.

RELATIONSHIP BETWEEN CERTAIN TYPES OF BATHOLITHS, CONTACT-METASOMATISM AND ORE DEPOSITION.

Browne (14) has usefully summarized the characteristics of batholiths, which, following Billings (9), he has divided into two types, synchronous and subsequent. The terms refer respectively to the contemporaneity or otherwise of the intrusion with orogenic epochs. Browne's summary is as follows:

Characters of Synchronous Batholiths.

Synchronous batholiths generally show all or most of the undermentioned characteristics:

(a) There is a constant association with schists or other regionally-altered and highly-folded rocks.

(b) Boundaries are steep or vertical in section, in plan parallel or sub-parallel with the strike of the enclosing rocks but often ill defined through gradation from the invading into the invaded rock; outcrops are markedly elongated parallel to the axis of folding, and peripheral lenses may be numerous.

(c) The roof is highly irregular, tending to fray out into sills and parallel lenses and tongues.

(d) Gneissic structure is commonly developed in the igneous rock, either primary alone or primary and secondary, the banding or foliation being parallel to the boundary of the intrusion and sometimes varied with minor crinkles and contortions.

(e) Abundant pegmatite is generally present, both as peripheral "lit-par-lit" injections and within the mass as contemporaneous stringers and as definite dikes.

(f) Inclusions are common, elongated parallel to the walls and the gneissic banding, and not deorientated.

(g) No hornfelsing of the country-rock has occurred, though this may have suffered much alteration through impregnation (granitization).

(h) There is little or no indication of serial differentiation in the intrusion, but pegmatite and gabbro dikes may appear, possibly as complementary differentiates;

dynamic differentiation through squeezing out of residual magma may also be apparent.

(i) Minerals like andalusite, sillimanite, cordierite, garnet and epidote may be present in the granitic igneous rocks, either through contamination or as primary crystallizations. Some local modification of the granite through incorporation of country rock may occur.

Characters of Subsequent Batholiths.

The following are the chief contrasting characters of subsequent batholiths:

(a) No necessary association with regionally metamorphosed rocks is observed; the country-rock may be only moderately folded.

(b) Boundaries are mostly sharp, and cross-cutting relations general, though there may be local concordance with the enclosing strata; outcrops are irregular in plan. Peripheral lenses are absent, but there may be dike- and still-apophyses.

(c) Indications may point to the roof having been fairly flat, or irregularly domed.

(d) The granite is in general massive, though marginally it may have directive structures.

(e) "Lit-par-lit" injection is scarce or absent, and there is a general scarcity of pegmatites, except as segregation veins, but fine-grained aplites are common, sometimes accompanied by lamprophyre dikes.

(f) Inclusions are angular and deorientated.

(g) Where the country-rocks have not suffered much previous metamorphism a contact aureole is present, with typical contact minerals, not usually, however, of very high-temperature formation.

(h) Extensive serial differentiation is indicated, often with evidence of more than one injection of magma.

(i) Contamination through incorporation of country-rock is not in general noteworthy.

Browne's and most other papers on this subject are based on the conception that granite is forced into the crust as a liquid which later crystallizes to a solid. If it is assumed, however, that the formation of a granite is a process of ultrametamorphism, with the direction of alteration being from sedimentary and volcanic rocks to metamorphic rocks, thence to banded granite and finally (in some cases) to magmatic granite, the picture, it is thought, becomes somewhat clearer.

The synchronous batholiths are those which, in general, have not reached the liquid-magmatic stage. They have been formed approximately in the position in which they are now found.

The subsequent batholiths have reached a sufficiently magmatic stage to have been moved subsequent to their formation. In many instances, banded granite of the synchronous type is found to be cut by bosses and dikes of massive granite, which, if they were larger, might be called subsequent batholiths. Relationships of this type do not necessarily imply a large time interval between the two "intrusives" as has been assumed by some magmatists.

Relationship to Ore Deposition.—Perhaps the most important characteristics of synchronous batholiths from the standpoint of the origin of ore deposits are:

(a) They are rich in pegmatites.
(b) They have associated with them metasomatic effects (impregnation and granitization of Browne), but heat effects (hornfelsing) are less pronounced.

In the writer's opinion, the process of contact metasomatism, the effects of which have been widely observed and described, is very much akin to the process which produces granite from sedimentary and other rocks. There is a vast exchange and re-arrangement of elements, but there is no melting or disturbance of the "intruded" rocks. Both processes could conceivably be due to solid diffusion, which is a function of temperature, to diffusion in liquids, and/or to the movement of aqueous solutions as proposed by Dunn (21).

Whatever the mechanism of the process of granitization, the point it is desired to make here is that the metasomatized zone at the edge of a synchronous granitic mass may well be regarded as a sample of the "front" of granitization which has moved through the sediments and other rocks, now converted into granite. The study of pyrometasomatic ore deposits (46 (b)) has shown that, when, for example, limestone occurs at the contact, there may be a movement of silica, iron and many ore minerals into the invaded rock and a great movement of lime into the granitic rock. The movement is not haphazard but directional, and implies the existence of some sort of gradient. The elements which cannot be accepted into the lattices of the newly-forming crystals of the granitic rock are segregated toward the margins of the granitized material. These processes take place at the time the granite is formed, not after the process of granitization has been completed. In some instances, however, the granitized material may become mobile and be forced upward by tectonic stresses. At this stage, the "magma" may cause heat metamorphism, but does not cause large-scale metasomatism.[13] Comparable effects are produced by masses of molten rock of "volcanic" origin.

Hence, on the granitization hypothesis; a more definite spatial relationship is to be expected between metasomatism and granite in the case of the synchronous batholiths than in the case of the subsequent batholiths. Similarly, pegmatites are accompaniments of granitization and their segregation would be expected in connection with the formation of synchronous batholiths. It is considered that the above relationships are not easy to explain if all granites are believed to have been forced into the crust in a liquid state, similarly to the mode of entry of rocks of volcanic origin.

Pyrometasomatic ore deposits result from special types of metasomatism, but these ore bodies may be considered as special types of the family of deposits genetically related to granitic rocks. If limestone or dolomite is present at the margin of the granite, these rocks appear to absorb the ore-forming materials. In the absence of limestone, and if suitable channelways are present, the ore-forming materials may travel upwards to form hypothermal and meso-

[13] If the granite becomes completely molten, it could absorb a large amount of water, as experiments (61 (d)) have shown. On crystallization, it would expel most of this water, along with other materials, and might thus cause some metasomatism. The effects produced in this way, however, do not appear to be comparable in magnitude with those produced during the conversion of the sedimentary and other rocks into granite. Possibly, the reason is that the mobile granite contains, for the most part, only materials of granitic composition, and thus, on crystallization, there is little to be expelled from the magma.

thermal deposits. Hence, it might be expected that aureoles of metasomatism—"la pénombre du granit" of Elie de Beaumont (20 (b)) and his contemporaries, the diabrochite of Dunn (21), and the "basic front" of Reynolds (59)—would show a relationship to the distribution of ore deposits, and that both would show a relationship to the occurrence of synchronous granite. Subsequent batholiths might not show these relationships.

Mount Painter, South Australia.—In the Mount Painter district, South Australia (66), where, during 1944 and 1945, the writer spent several months, there are two granites of different age. The older is known as the red granite and consists for the most part of quartz and reddish microcline, the color being due to inclusions of hematite. Ferromagnesian minerals are typically absent, but bands of biotite-rich rock are found at short intervals. Throughout its mass, this granite contains numerous bands of partly altered sediments and there are all gradations from unaltered sediments to solid granite. Along one margin of the main mass is a zone of felspathized quartzite up to two miles wide. Bedding outcrop lines may, in many instances, be traced from unaltered sediments into the granite, and there appears to have been little, if any, disturbance of the sedimentary structures during granitization. This granite has the characteristics of a synchronous batholith, and, to the field observer, there appears to be little room for doubt that the granite has formed by a replacement process.

The red granite is cut by numerous dikes and bosses of white massive granite which has a composition generally similar to that of the red granite, but does not contain the abundance of hematite which gives the red granite its characteristic color. Dikes of white granite follow joint-like openings in the red granite and, in some instances, they have also been controlled by remnants of bedding in the red granite. In others, the white granite has invaded sedimentary areas lying apart from the red granite. If these intrusions were larger, they would perhaps be called subsequent batholiths.

Deposits of copper, gold, bismuths, antimony and tungsten occur almost exclusively about the margins of the red granite mass. In addition, uranium and thorium-bearing minerals were found in pegmatites and in crush zones in the red granite mass only.

Brocks Creek, Northern Territory.—In the Brocks Creek district, Northern Territory, Australia (64), concordant granites, forming the cores of eroded domes and anticlines, are ringed by marked zones of metasomatism, represented by graphite-schists, hematite-rich rocks and amphibolites which seem to have been formed by replacement of sediments. The general relationships suggest that, just as in a regional sense folded rocks only are replaced by granite, only the more tightly folded portions of the generally folded area have been granitized.

At Brocks Creek only minor gold and copper mineralization are found around the margins of the eroded granite, but relatively important gold-arsenopyrite-pyrite replacement deposits are found on other domes and anticlines, in the vicinity of which no granite is outcropping. The deposits, however, are associated with graphitic schists, hematite-rich rocks and amphibolites, and it seems a valid inference that they lie in the metasomatic aureole of

granite cupolas occurring at depth. After detailed mapping, it was found that the hematite-rich beds, the amphibolites and the ore deposits all occur at approximately the same stratigraphic horizon. This would not have been suspected without careful mapping, as there has been considerable displacement by post-ore faulting and over 50 percent of the area is covered by soil.

Similar relationships have been found at intervals in an area of approximately 5,000 square miles surrounding the Brocks Creek district. This area is occupied by the same series of sediments as that at Brocks Creek and contains a number of synchronous batholiths. A plan has been formulated to prospect this region using the relationships found in the Brocks Creek district. The search for ore will be localized on domes and anticlines in the vicinity of known favorable horizons and close to metasomatized rocks which appear to indicate the presence of granite below.

Broken Hill, N. S. W.—Application of similar ideas could be useful at Broken Hill, N. S. W., where Andrews (2) has shown that the granites are almost exclusively of the synchronous (formed in situ?) type, and where the known ore body occurs on an anticline which itself has been largely granitized. The ore is intimately associated with pegmatite. Browne (14) summarizes the geology of the area as follows:

> The Willyama (Archeozoic) Series, dominantly of pelitic sediments, was highly metamorphosed and folded, and injected by granitic gneisses, with accompanying gabbros and pegmatites. The granites and some of the gabbros have a marked primary gneissic structure, often with a cataclastic foliation superimposed. The sill-habit is by far the most common for both acid and basic rocks about Broken Hill. . . . Transgressive boundaries are practically, if not entirely unknown, and indeed, the structures of domes and basins in the sedimentary series are indicated by the intercalated sills of granite and gabbro.

The present writer has spent only a week in the Broken Hill district, but from the observations made then, from the mapping of Andrews and from other work (unpublished), it appears not unlikely that most of the so-called igneous rocks, including the basic ones occurring in the vicinity of the ore deposits, have been formed by the metasomatic alteration of sediments and that, in effect, the ore body occurs within the femic metasomatic aureole of a granite cupola formed at some depth by replacement of a tightly compressed anticline.

If this view is correct, the search for non-outcropping deposits should be, in some respects, a search for further buried granite cupolas, the areas above which have widely been recognized as being favorable for ore; in this search the presence of an amphibolite, for example, may have important significance when considered in the light of "basic front" principles (59).

The Broken Hill lead-zinc lode is intimately associated with pegmatites and appears to have been emplaced during a period of granitization. The main section of the deposit is confined to certain beds which, in cross-section, are compressed into an anticline, and, in longitudinal section, from a broad arch. Only the central portion of the arch outcropped and probably a further 1,000 to 1,500 feet of rock cover would have obscured the deposit entirely. However, there would have been an outcrop of the metasomatized rocks which are found above the present non-outcropping portions of the lode.

Spectrochemical studies by Stevenson (67) show, as would be expected, that there is a regular change in the minor-element content of a hornfelsed tuff as a granodiorite contact is approached. Similar studies of the rocks lying above the non-outcropping portions of the Broken Hill lode might serve to identify the zone of metasomatism and to enable this zone to be recognized if it outcrops in other tightly folded areas in the district (65). As the studies of Lapadu-Hargues (59) have shown, the outward migration of elements from a theatre of granitization is not a haphazard process, but is related, for one thing, to the atomic size of the elements. In some instances, the metamorphic aureole around granitic masses extends over a width of 1 to 2 miles, so that there is a wide range of alteration to be studied.

General Application.—The recognition that, in areas containing synchronous granites, replacement deposits may be found at approximately the same stratigraphic horizon is itself important. This may explain occurrences such as the Rhodesian-Belgian Congo copper deposits, which remain within a limited stratigraphic range over long distances. According to Davidson's (19) description, the granites of the area are of the synchronous type, and at the Chambishi Mine, at least, there is a close relationship between granite and ore.

The differences between synchronous and subsequent granites may also explain certain apparently anomalous relationships which have caused perplexity in the past. Lindgren (46 (c)), in his review of the metasomatic magnetite deposits of Sweden, notes that, although the ore occurrences are associated with leptites and "skarn" and show undoubted metasomatic characteristics, the granite actually adjoining the deposits is younger than they are, and has not given rise to important metasomatism. This suggests a case in which metasomatism took place above a theatre of granitization; later, the granite became magmatic and was forced upward, but, at this stage, it did not greatly affect the ore deposits or the surrounding rocks.

Similarly, in the Brocks Creek district, already referred to, a discordant granite has cut higher formations in the stratigraphic column than that reached by the concordant granite and has also truncated a metasomatic aureole, believed to have been formed above a granite cupola. The cross-cutting (subsequent) granite has no marked zone of metasomatism associated with it, nor does it show any definite spatial relationship to the ore deposits. The sediments bordering the cross-cutting granite show, in the main, the effects of thermal metamorphism.

GENETIC CLASSIFICATION OF ORE DEPOSITS.

The concepts outlined in the preceding sections lead naturally to the conclusion that there is an inherent difference between ore deposits associated with granitization and those associated with "volcanic" activity, whether that "volcanic" activity results in the formation of tin deposits as in Bolivia, of copper deposits as in Michigan or at Whim Creek, Western Australia, of nickel-copper deposits as at Sudbury, or of tungsten deposits as in Boulder County, Colorado (48). This difference was not emphasized by Lindgren

(46), though several authors (52, 43 (b)) have pointed out that his epithermal class is generally genetically related to "volcanic" activity.

It is misleading to classify a lithophile granitization deposit formed at low temperature, such as the uranium deposit at Great Bear Lake, Canada, with low-temperature chalcophile deposits, such as those of the San Juan Region, Colorado, or the native copper deposits of Lake Superior, whose origin, along with that of the associated volcanic rocks, would seem to lie below the lithosphere. The true "volcanic" ore deposit does not contain appreciable amounts of lithophile elements, although it may contain elements—*e.g.*, tin—normally deposited at high temperature. There is a still greater distinction between granitization deposits and those exclusively associated with ultrabasic rocks, *e.g.*, platinum, chromite and diamond. These apparently originate far below the lithosphere.

Several authors have noted that massive sulphides are not common in deposits related to the granitic rocks, whereas basic dikes (volcanic origin) commonly introduce massive sulphide deposits. This distinction may be related to the fact that sulphur is a chalcophile element and is not abundant in the normal geosynclinal pile; generally there is not enough sulphur present to satisfy the total iron content in excess of that required to satisfy the rock-forming minerals of the final granite, and so, during granitization, iron expelled from sediments and "volcanic" rocks may be concentrated in rock-forming minerals or in the form of oxides. Consideration of the fact that the sulphur content of sedimentary piles may vary considerably may lead to a better understanding of metallic-oxide and silicate deposits such as those at Franklin Furnace, New Jersey, and at Langban (46 (c)) and other places in Sweden. There is some evidence, also, that sulphides tend to be segregated in the regions overlying areas undergoing granitization while the less volatile oxides are commonly found at the sides of the granitized rocks (64).

It has been common practice in the past to attribute all ore deposits to granite, whether the latter is actually visible in the region or not. Thus the ores of the Mount Bischoff-Renison Bell tin field, Tasmania (69), are obviously related to quartz-porphyry dikes, and it has been assumed that these porphyries are of granitic origin. However, the ore deposits themselves are quite different from those normally related to granite, as the cassiterite is in fine-grained aggregates and is associated with massive sulphides (pyrite and pyrrhotite). Carbonate gangue is abundant, and the presence of such minerals as tetrahedrite, jamesonite, stannite, and canfieldite, taken together with the above characteristics, links these deposits with some of those in Bolivia of "volcanic" origin. It would not be unexpected to find that the quartz-felspar-porphyries are in reality differentiates formed during the cycle of predominantly basic "volcanic" activity which occurred in this region. Massive sulphides are uncommon in tin deposits related to granite batholiths.

Evidence from the Noranda-Kirkland Lake area (70) suggests that, in this locality, regional faults are more important than intrusives in determining the character and distribution of mineral deposits. During the past two years the writer has noted similar features in the Cobar District, N. S. W. (65), where structures of a regional character appear to have localized a copper-

gold province. No granite rocks occur within 20 miles of Cobar, yet, in the past, geologists have unanimously attributed the ore to granite "occurring at depth." There is much evidence of "volcanic" activity more or less contemporaneous with the ore deposition.

Is it not possible that, in cases such as these, deeply penetrating lines of weakness have reached sources of metals from below the solid crust? This would seem to be especially possible in volcanic regions where the crust had been temporarily thinned, *i.e.*, where the geoisotherms had risen unusually close to the surface. At Cobar, ores theoretically belonging to various depth zones occur alongside each other, although it is considered that essentially there is only one period of mineralization. Perhaps this implies fluctuation in the depth of the geoisotherms. The lack of zoning might not be expected if the ores had originated from a granitic batholith, cooling slowly "at depth."

CONCLUSIONS.

De Beaumont (20 (c)) remarked that the study of the origin of granitic rocks is an indispensable counterpart of the study of the origin of ore deposits. The conception of "ortho-magmatic differentiation" led to certain hypotheses regarding the origin and behavior of ore deposits but these hypotheses must be reconsidered if the possibility is admitted that granitic rocks may have been formed mainly from crustal material by a process of "granitization" such as that described by Backlund (3).

As a contribution to this reconsideration of outlines of five main concepts are put forward in this paper:

(1) During the first cooling of the earth the elements were distributed according to geochemical laws outlined by Goldschmidt (34). Geochemical equilibrium evidently required the formation of a granitic crust. The later addition to the crust of basic volcanic rocks set up a chemical gradient. Granitization represents the neutralization of this gradient—the approximate return to the geochemical equilibrium attained at the first earth cooling.

(2) Magmatic differentiation and erosion do not adequately explain the distribution of granitic rocks and of ore deposits in geological time. The granitization hypothesis, when the effects of "volcanic" activity are considered, supplies a possible explanation.

(3) The associations of specific ores with specific types of granitic rocks do not necessarily imply the correctness of the theory of "magmatic differentiation." During the formation of a granitic rock, those elements are concentrated which are not accepted into the crystal lattices of the common rock-forming minerals. The concentration of particular elements by particular rocks will, presumably, occur whether the rock crystallizes from a melt, or whether the crystallization results from the re-arrangement of atoms by some other processes—*e.g.*, by diffusion in the solid (58).

(4) The differences between synchronous and subsequent batholiths become intelligible in the light of the granitization hypothesis. Synchronous granites show a close spatial relationship to contact metasomatism and to ore deposition; the two latter processes are intimately connected with each other. In areas where synchronous granites occur, these facts may be used to guide prospecting; in particular they may be used to localize ore search over non-outcropping granite cupolas.

(5) The granitization hypothesis postulates a fundamental difference between granitic and "volcanic" rocks: similarly, ore deposits originating during a cycle of granitization are basically different from those of "volcanic," or abyssal, origin.

Among these differences are the relative scarcity of lithophile ore elements in "volcanic" deposits; the relatively high sulphur content of many of the "volcanic" deposits; and the lack of zonal arrangement in "volcanic" deposits as compared with deposits associated with granitization.

ACKNOWLEDGMENTS.

The author is greatly indebted to officers of the Bureau of Mineral Resources, Geology and Geophysics, especially Dr. H. G. Raggatt, Dr. N. H. Fisher and Dr. J. A. Dunn, who have read and criticized this paper. Special thanks are due to Mr. W. B. Dallwitz for careful checking of the manuscript and for many helpful suggestions.

Bureau of Mineral Resources,
Geology and Geophysics,
Canberra, N. S. W., Australia,
April 22, 1948.

BIBLIOGRAPHY

1. Anderson, J. S., Chemistry of the earth: Royal Soc. New South Wales Jour., vol. 76, p. 339, 1942.
2. Andrews, E. C., The geology of the Broken Hill District: New South Wales Geol. Survey, Mem. 8, 1922.
3. Backlund, H. G., The granitization problem: Geol. Mag., vol. 83, pp. 105–117, 1946.
4. Baker, J. S., World survey of tantalum ore: U. S. Bur. Mines Inf. Circ. 7319, 1945.
5. Bastin, E. S., Aplites of hydrothermal origin associated with Canadian cobalt-silver ores: Econ Geol., vol. 30, pp. 715–734, 1935.
6. Bateman, A. M., Economic Mineral Deposits, (a) pp. 326–327; (b) pp. 542–543; (c) pp. 59–66; (d) p. 599, New York, 1943.
7. Bateman, A. M., Magmas and ores: Econ. Geol., vol. 37, pp. 1–15, 1942.
8. Bichan, W. J., The ubiquity of gold values: Econ. Geol., vol. 42, pp. 376–403, 1947.
9. Billings, M. P., The petrology of the North Conway quadrangle in the White Mountains of New Hampshire: Am. Acad. Arts and Sci. Proc., vol. 63, p. 67, 1928.
10. Bragg, W. L., Atomic Structure of Minerals, pp. 37–40, Cornell University Press, 1937.
11. Bray, J. M., Spectroscopic distribution of minor elements in igneous rocks from Jamestown, Colorado: Geol. Soc. America Bull., vol. 53, pp. 765–814, 1942.
12. Broderick, T. M., Hohl, C. D., and Eidemiller, H. N., Recent contributions to the geology of the Michigan copper district: Econ. Geol., vol. 41, pp. 712–713, 1946.
13. Browne, W. R., An outline of igneous action in New South Wales till the close of the Paleozoic Era: Linnean Soc. New South Wales Proc., vol. 54, pp. 9–39, 1929.
14. Browne, W. R., Notes on batholiths and some of their implications: Royal Soc. New South Wales Jour. and Proc., vol. 65, pp. 112–114, 1931.
15. Buddington, A. F., Correlation of kinds of igneous rocks with kinds of mineralization: Ore deposits of the Western United States, A.I.M.E., pp. 350–385; (a) p. 353, New York, 1933.
16. Campbell, D. F., The Oruro silver-tin district, Bolivia: Econ. Geol., vol. 37, pp. 87–115, 1942.
17. Clarke, F. W., The data of geochemistry: U. S. Geol. Survey Bull. 770, p. 29, 1924.
18. Daly, R. A., Igneous Rocks and the Depths of the Earth, (a) p. 9; pp. 43–45, 1933.
19. Davidson, D. M., The geology of Chambishi, Northern Rhodesia: Econ. Geol., vol. 26, pp. 131–152, 1931.
20. De Beaumont, Elie, Note sur les émanations volcaniques et métallifères: Soc. géol. France, (a) p. 1301; (b) p. 1295; (c) pp. 1290–1291, 1847.
21. Dunn, J. A., Granite and magmation and metamorphism: Econ. Geol., vol 37, pp. 231–238. 1942. Also: India Geol. Survey Mem., LXIX (2), pp. 447–451.
22. Ellis, H. A., The geology of the Yilgarn Goldfield South of the Great Eastern Railway: West. Australia Geol. Survey Bull. 97, 1939.
23. Emmons, S. F., Gold Deposits of the World, pp. 333–349, New York, 1937.
24. Evans, D. L., Structure and mineral zoning of the Pailiviri Section, Potosi, Bolivia: Econ. Geol., vol. 35, pp. 737–750, 1940.

25. Fairbairn, H. W., Packing in ionic minerals: Geol. Soc. America Bull., vol. 54, pp. 1305–1374, 1943.
26. Ferguson, H. G., and Bateman, A. M., Geologic features of tin deposits: Econ. Geol., vol. 7, pp. 209–262, 1912.
27. Finucane, K. J., and Sullivan, C. J., The Whim Well and Mons Cupri copper mines, Pilbara goldfield: Australia, Aerial, Geol. & Geophys. Surv. N. Australia, Rept. W. Australia no. 55, 1939.
28. Finucane, K. J., The Braeside lead field, Pilbara District: Australia, Aerial, Geol. & Geophys. Surv. N. Australia, Rept. W. Australia no. 24, 1938.
29. Finucane, K. J., Preliminary report on geological survey of the Read-Rosebery District. Tasmania: Chem. Eng. and Min. Rev., Oct. and Nov. 1932. (Much unpublished later information is now available.)
30. Finucane, K. J., and Jones, F. H., The Barker River area, West Kimberley District: Australia, Aerial, Geol. & Geophys. Surv. N. Australia, Rept. W. Australia no. 43, 1939.
31. Finucane, K. J., East-dipping strike-faults on the Boulder Belt, Kalgoorlie: Australasian Inst. Min. Metallurgy Proc., n. s. no. 124, (a) pp. 209–210; (b) p. 203, 1941.
32. Turneaure, F. S., Tin deposits of Llalagua, Bolivia: Econ. Geol., vol. 30, pp. 170–190, 1935.
33. Gallagher, David, Albite and gold: Econ. Geol., vol. 35, pp. 698–736, 1940.
34. Goldschmdit, V. M., The principles of distribution of the chemical elements in minerals and rocks: Chem. Soc. London Jour., pp. 655–673, 1937.
35. Gummer, W. K., and Burr, S. V., Nephelised paragneisses of the Bancroft area, Ontario: Jour. Geology, vol. 54, pp. 137–168, 1946.
36. Gustafson, J. K., and Miller, F. S., Kalgoorlie geology re-interpreted: Econ Geol., vol. 32, pp. 285–317; (a) p. 295; (b) pp. 293–294, 1937.
37. Harcourt, G. A., The minor chemical constituents of some igneous rocks: Jour. Geology, vol. 42, pp. 585–601, 1934.
38. Hevesy, G., and Hobbie, R., Lead content of rocks: Nature, vol. 128, pp. 1039–1040.
39. Holmes, Arthur, An estimate of the age of the earth: Geol. Mag., vol. 84, pp. 123–126, 1947.
40. Johannsen, Albert, A Descriptive Petrography of the Igneous Rocks, (a) vol. 2, p. 151; (b) vol. 4, p. 212; (c) vol. 4, p. 105, University of Chicago Press, 1941.
41. Kenney, E. J., and Mulholland, C. St. J., The ore deposits of Captain's Flat, New South Wales: Australasian Inst. Min. Metallurgy Proc., n. s. no. 122, p. 102, 1939.
42. Kidd, D. F., and Haycock, M. H., Mineragraphy of the ores of Great Bear Lake: Geol. Soc. America Bull. 46, no. 6, pp. 879–959, 1935.
43. Laughlin, G. F., and Behre, C. H., Jr., Classification of ore deposits: Ore deposits of the Western United States, A.I.M.E., (a) p. 40; (b) p. 52, New York, 1933.
44. Li, K. C., and Wang, C. Y., Tungsten, pp. 4–92, New York, 1943.
45. Lindgren, W., Differentiation and ore deposits in the Cordilleran region of the United States: Ore deposits of the Western United States, A.I.M.E., pp. 152–180, New York, 1933.
46. Lindgren, W., Mineral Deposits, 4th Ed., (a) p. 659; (b) 695–761; (c) pp. 739–743, 1933.
47. Locke, Augustus, Granite and ore: Econ. Geol., vol. 36, pp. 448–454, 1941.
48. Lovering, T. S., The origin of the tungsten ores of Boulder County, Colorado: Econ. Geol., vol. 36, pp. 229–279, 1941.
49. Mawdsley, J. B., Late gold and some of its implications: Econ Geol., vol. 33, pp. 194–210, 1938.
50. Moore, E. S., Genetic relations of gold deposits and igneous rocks in the Canadian Shield: Econ. Geol., vol. 35, pp. 127–139, 1940.
51. Newhouse, W. H., The geology and ore deposits of Buchans, Newfoundland: Econ. Geol., vol. 26, pp. 399–414, 1931.
52. Niggli, Paul, Ore Deposits of Magmatic Origin (transl. by H. C. Boydell), (a) pp. 49–68; (b) p. 69; (c) pp. 68–82, 1929.
53. Palache, Charles, Berman, Harry, and Frondel, Clifford, Dana's System of Mineralogy, vol. 1, (a) pp. 614–615; (b) p. 676; (c) p. 557; (d) p. 691, New York, 1944.
54. Rastall, R. H., The granite problem: Geol. Mag., vol. 82, pp. 19–30, 1945.
55. Rastall, R. H., The significance of variation in granites: Geol. Mag., vol. 84, pp. 29–32, 1947.
56. Read, H. H., Meditations on granite I and II: Geol. Assoc. Proc., vol. 54, pp. 64–85; vol. 55, pp. 45–93, 1943–44.
57. Reynolds, D. L., Geochemical changes leading to granitization: Geol. Soc. London Quart. Jour., vol. 102, pp. 389–446, 1946.

58. Reynolds, D. L., The granite controversy: Geol. Mag., vol. 84, pp. 216–218, 1947.
59. Reynolds, D. L., On the relationship between "fronts" of regional metamorphism and "fronts" of granitization: Geol. Mag., vol. 84, pp. 106–109, 1947.
60. Scrivenor, J. B., The Geology of the Malayan Ore Deposits, pp. 2–3, London, 1928.
61. Shand, S. J., Eruptive Rocks, 2nd Ed., (a) pp. 261–265; (b) pp. 357–382; (c) pp. 268–269; (d) pp. 38–39, London, 1943.
62. Shimer, J. A., Spectroscopic analysis of New England granites and pegmatites: Geol. Soc. America Bull., vol. 54, pp. 1049–1066, 1943.
63. Sullivan, C. J., Mineral resources of Australia, Summary Report no. 18, Beryllium, 1945.
64. Sullivan, C. J., Relationship between ore and general geology, Brocks Creek District, Northern Territory: Australasian Inst. Min. Metallurgy Proc. (to be published shortly).
65. Sullivan, C. J., Geology as an aid to ore-finding: Chem. Eng. and Min. Rev., pp. 95–100, Dec. 1946.
66. Sullivan, C. J., Sprigg, R. C., and Others: Investigation of uranium deposits at Mount Painter, South Australia, 1944–45 (unpublished report).
67. Stevenson, J. S., The geology of the Red Rose tungsten mine, Hazelton, British Columbia: Econ. Geol., vol. 42, pp. 434–464, 1947.
68. Stillwell, F. L., Geology and ore deposits of the Boulder Belt, Kalgoorlie: West. Aust. Geol. Survey Bull. 40, (a) pp. 66–69; (b) p. 43; (c) pp. 43–50; (d) pp. 34–36, 1929.
69. Stillwell, F. L., and Edwards, A. B., Mineral composition of the tin ores of Renison Bell, Tasmania: Australasian Inst. Min. Metallurgy Proc., n. s. nos. 131 and 132, pp. 173–186, 1943.
70. Thomson, J. E., Structure and ore deposits of the Kirkland Lake, Noranda, Val D'Or belt, Ontario and Quebec: Econ. Geol., vol. 42, p. 412, 1947 (Abstract).
71. Twenhofel, W. H., Treatise on Sedimentation, 2nd Ed., p. 290, 1932.

METAMORPHIC GRADIENT, KENT COALFIELD, ENGLAND.

H. W. WELLMAN.

ABSTRACT.

Coal analyses from bores and shafts within the Kent coalfield England show that not only does the average percentage of volatile matter decrease with increasing depth, but that the rate of decrease progressively decreases towards the present centre and high-rank part of the coal basin. This change in rate is apparently due to differences in the geothermal gradient and cannot be explained by the uniformly gentle deformation of the coal measures. The geothermal gradient is thought to have decreased towards the centre of the basin at the time of greatest burial, in the same way as geothermal gradients usually decrease towards areas of thicker sediments at the present time.

INTRODUCTION.

WHILE studying the cause of coal metamorphism in New Zealand I was led to the conclusion that the rate at which the rank of coal changes with depth (vertical metamorphic gradient) is the most significant and universal feature of coal metamorphism. The well defined change in the value of this gradient at the Kent coalfield was discovered while searching the literature for established gradients from other parts of the world. Critical gradient analyses are available only from places where deep bores or shafts have penetrated thick coal measures, and only with high rank bituminous coal or anthracite is volatile matter alone sufficient to define coal rank. Kent coalfield contains only high rank bituminous coal and has been penetrated by numerous well distributed bores and shafts.

Three papers describing the coalfield are given in the *Summary of Progress of the Geological Survey of Great Britain for the year 1932*. The first by Dines deals with the sequence and structure, the second by Crookall with the fossil flora, and the third by Stubblefield with the fauna. The coalfield is a considerable distance from the English coalfields and possibly extends beneath the English Channel to connect with the Pas de Calais coalfield in France. The coal measures, Yorkian, Staffordian, and Radstockian in age, were gently folded and elevated probably at the end of the Paleozoic. A peneplain cuts across folded coal measures and older rocks alike was later depressed beneath the sea and received a relatively thin Mesozoic and Tertiary cover which now rests with slight angular unconformity on the coal measures. The coalfield although described as a basin is a syncline trough in which the lower part of the coal measures was protected from erosion, the basinward thickening of individual beds making up only a small part of the total thickening.

The tabulated volatile percentage of seams from seven bores and two shafts on a north-east cross-section (Dines, Table B) provides the sole source of the analytical material in this paper. Dines states (p. 36):

The coals, spread over a vertical thickness of about 2,800 feet of strata, show a considerable vertical variation in volatile content, the values decreasing with increase in depth. Examples are given in Table B which shows the volatile values for seams in certain of the sections. It will be seen that, though the decrease in volatile matter with increase in depth is a general rule, there are occasional seams which give a higher value than the seams above or below them. Curve charts showing the volatile matter plotted against the depths of the seams do not appear to reveal more than the fact that there is a general falling off of volatile matter in depth. The occasional high values are not confined to any one horizon or depth. They may be due, in some cases, to analytical discrepancies, possibly caused by the fact that a sample obtained from a borehole was not truly representative of the seam.

Dines concludes his remarks on the analyses (p. 37) by stating:

As far as can be seen from the data available, there does not appear to be any phenomenon which would explain the distribution of the volatile values. A view is held that the volatiles are, to some extent, dependent upon the depth of the seam below surface. This theory does not agree with the conditions in Kent today, but it is possible that the present distribution of the volatile values was determined by a cover of strata overlying the Coal Measures, which was removed before the present cover of Jurassic, Cretaceous and Tertiary rocks was laid down.

Dines' suggestion that coal rank was controlled by beds that were eroded prior to the deposition of the Mesozoic and Tertiary cover is the first step in an explanation of the rank distribution. The covering beds are less indurated and have a higher moisture content than the coal measures. They are now about 1,000 feet thick and there is no evidence that they have been reduced by more than a thousand feet by post-Tertiary erosion. Were there coal present at the base it is almost certain that it would be either lignite or low rank sub-bituminous. Thus, the unconformity at the base of the covering strata not only marks a long period of time but also coincides with a jump in metamorphism great enough to suggest that the thickness prior to the deposition of the cover must have been considerably greater than the maximum thickness of the cover itself. According to the explanation adopted here the thickness of the missing sub-bituminous and high volatile bituminous zone will equal the difference in thickness between cover and eroded coal measures. A rough evaluation of this thickness is given later.

MEASUREMENT OF VERTICAL METAMORPHIC GRADIENTS.

Before discussing vertical metamorphic gradients it is essential to have some uniform way of measuring them. The vertical metamorphic gradient is usually expressed as the change in volatile percentage per unit depth, often without definite reference to the composition of the coal; a value of 6 per cent decrease per thousand feet being sometimes given as an average value for bituminous coal. Laboratory and field data both suggest exponential rather than uniform rate of decrease. Cannon and co-workers [1] studied the thermal devolatilization of coal in the laboratory and presented a chart showing the relation between volatile content and temperature. Coals of different ranks

[1] Cannon, C. G., Griffith, M., and Hirst, W., The carbonisation of coal, *in* The ultra-fine structure of coals and cokes: The British Coal Utilisation Research Association, 1944.

show little change in volatile content until their particular decomposition-temperature is reached. Volatile matter is then given off, rapidly at first and then at a progressively less rapid rate. Although decomposition-temperature increases with increase in rank and the lower temperature parts of the curves differ, the higher temperature (exponential) parts almost coincide, showing that a uniform increase in temperature causes volatile matter to be given off from all the coals tested at the same progressively decreasing rate. Although

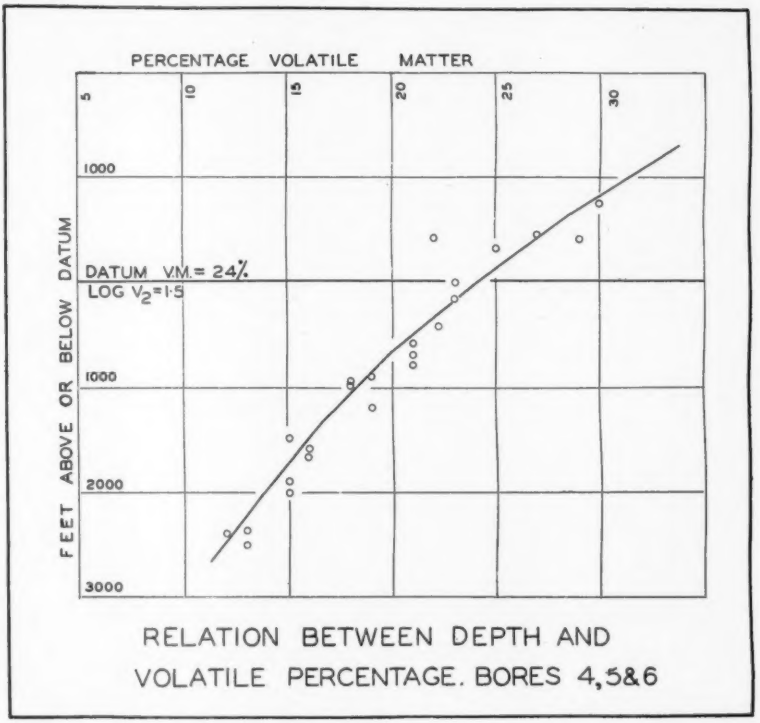


FIG. 1.

it is most unlikely that the laboratory relation between temperature and volatile content applies to coals being devolatilized deep within the earth under progressive increase of *both* pressure and temperature, the decrease in rate in the laboratory under atmospheric pressure is probably significant also for conditions within the earth under increasing pressure.

Indirect but strong evidence is provided by the particular special relations of coals of different ranks, the degree of association of coals of successive

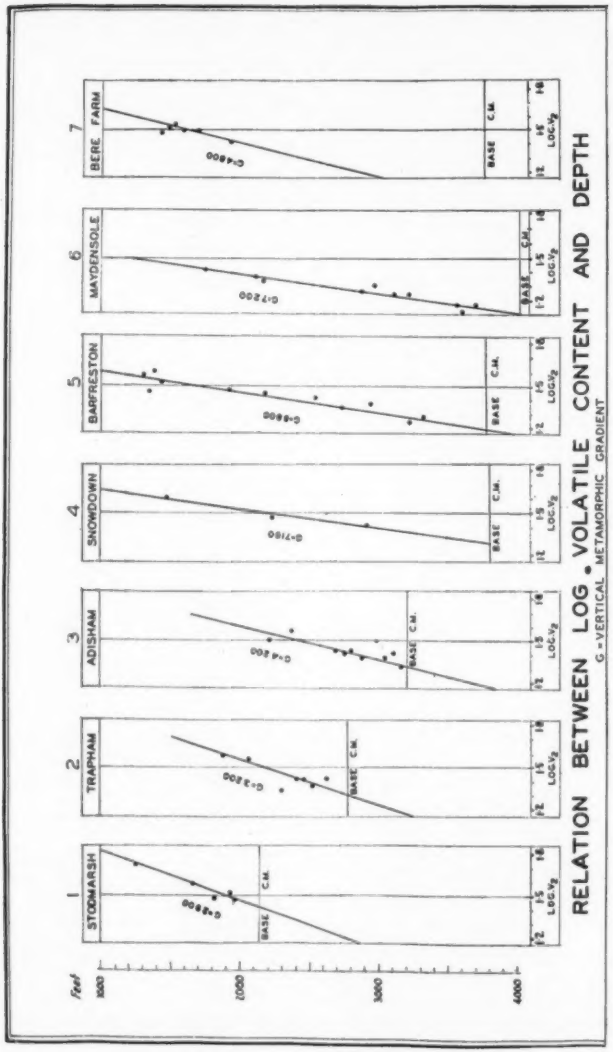
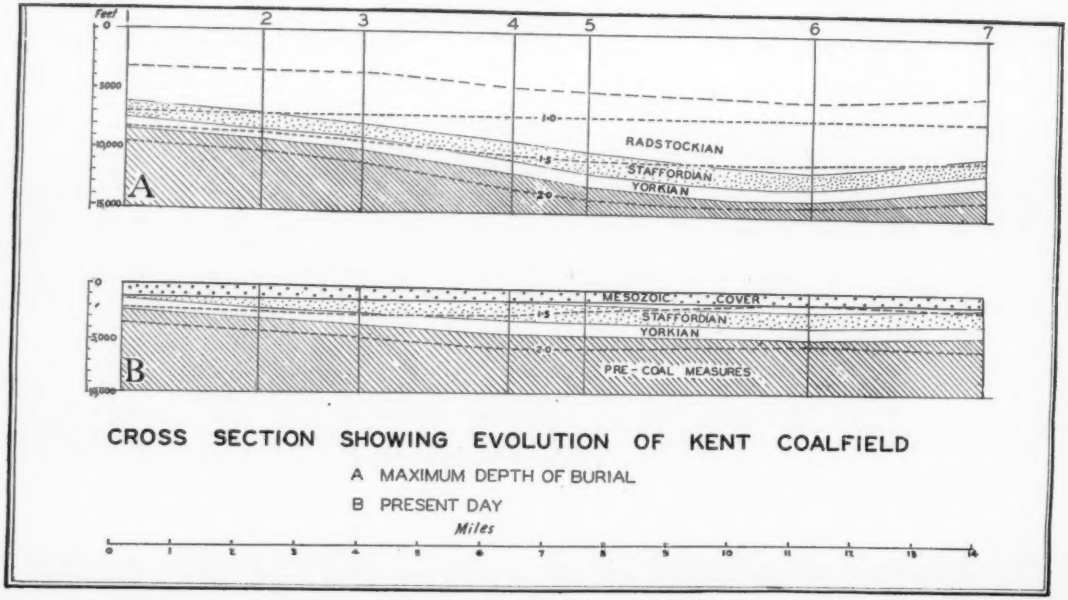

RELATION BETWEEN LOG. VOLATILE CONTENT AND DEPTH
G = VERTICAL METAMORPHIC GRADIENT
Feet
1000
2000
3000
4000
1 STODMARSH
2 TRAPHAM
3 ADISHAM
4 SNOWDOWN
5 BARFRESTON
6 MAYDENSOLE
7 BERE FARM
BASE C.M.
1·2 1·5 1·8 LOG. V%

FIG. 2.



CROSS SECTION SHOWING EVOLUTION OF KENT COALFIELD

A MAXIMUM DEPTH OF BURIAL

B PRESENT DAY

FIG. 3.

ranks being shown by the limited range of coal ranks within particular coalfields. For instance many coalfields range from lignite to sub-bituminous, many from sub-bituminous to medium volatile bituminous, many from medium volatile bituminous to low volatile bituminous, and many from low volatile bituminous to anthracite, but none from anthracite to graphite. Yet the difference in volatile content between anthracite and graphite is only a few percent.

Quantitative evidence provided by Hickling [2] shows that the rate at which the volatile matter is reduced with depth is more than twice as rapid for lower rank English seams as for the higher rank Welsh bituminous coals and anthracites.

The three deepest bores in the Kent coalfield although penetrating only a small range of coal ranks provide significant evidence for a decrease in the rate at which percentage volatile matter is reduced with depth. The metamorphic gradient of these three bores is very similar (Fig. 2) and by adjusting them to a common datum they can be combined into one diagram. Twenty-four percent volatile matter (Log. $V_2 = 1.5$) is a convenient depth datum, and depth above or below this datum has been plotted against percentage volatile matter in Figure 1. In spite of considerable scatter the graph indicates a significant decrease in the rate at which volatile matter is reduced with depth. The curved line in this diagram represents the adopted exponential relationship for the average metamorphic gradient of these three bores.

Theoretical considerations determine the best form of exponential expression. The reduction in coal mass during progressive metamorphism makes it desirable to relate volatile matter to some constant rather than to adopt the usual procedure of expressing it as a percentage of varying mass. Fixed carbon although probably not strictly constant is the only determined coal constituent that is not certainly reduced in mass during metamorphism. The symbol V_2 is used in this paper for volatile matter expressed as a percentage of fixed carbon, V_2 being related to V_1, the percentage volatile matter (dry ash free basis), as follows:

$$V_2 = \frac{V_1 \times 100}{\text{F.C.}}.$$

A convenient measure of the metamorphic gradient for any particular bore or shaft is that depth in which Log. V_2 is reduced by one unit, that is the depth in which V_2 is reduced tenfold (from say 12 to 1.2). This measure of metamorphic gradient satisfies the limited laboratory and field data.

(1) Temperature differences are proportional to Log. V_2 differences during thermal decomposition at atmospheric pressure, the numerical values of Cannon and co-workers being reduced to straight lines when replotted in logarithmic form.

(2) The English and Welsh gradients given by Hickling become almost equal when expressed as differences in Log. V_2.

[2] Hickling, H. G. A., The properties of coal as determined by their mode of origin: Jour. Inst. Fuel, 1932.

(3) The curved line representing the average gradient for the three deepest Kent columns is reduced to a straight line when Log. V_2 content is plotted against depth.

(4) The Log. V_2 difference between a graphite with 0.7 percent volatile matter and an anthracite with 7 percent is the same as that between the anthracite and a 40 percent bituminous coal. Field relations show graphite no more closely associated with anthracite than indicated by this log. difference.

Having shown that the logarithmically defined gradients satisfy the available data which cover a wide range of ranks, it is reasonable to assume that errors will be negligible when extrapolating from the generalized gradients of the Kent coalfield within this range.

The Log. V_2 values of the volatile percentages given by Dines have been plotted against depth in Figure 2, the columns representing individual bores and shafts having been arranged in Dines' original north-west order. Average gradient lines drawn by estimation through the analytical points show decreasing slope away from the deepest part of the syncline, successive difference in slope being in general less than the probable error of individual gradients. Such a regular increase in metamorphic gradient cannot be due to chance and must be due to an equally regular increase in the metamorphic factors that cause increase of rank with depth, these factors being related in a regular way to the present structure.

If this relation between vertical metamorphic gradient and present structure should prove to be general it will confirm and expand the scope of Hilt's Law. In any case within the Kent coalfield it provides a critical test of rival theories of coal metamorphism.

CAUSE OF METAMORPHISM.

The following facts established in the Kent coalfield have to be considered:

(1) Coal metamorphism is a regional feature, average coal rank changing gradually both vertically and horizontally.

(2) The rank of each coal seam continuously decreases away from the present center of the basin.

(3) The vertical metamorphic gradient continuously increases away from the center of the basin.

(4) The coal measures not only thin towards the edge of the basin through synclinal folding and subsequent erosion, but also to a lesser extent through thinning of individual beds.

(5) Deformation is uniformly slight over the whole field.

Only two commonly accepted theories of *regional* coal metamorphism have been proposed. The first by Hilt, later re-affirmed by Heck[3] and Hickling,[2] emphasizes the vertical metamorphic gradient and suggests depth of burial with the associated temperature and pressure gradients as the cause.

[3] Heck, E. T., Regional metamorphism of coal in southeastern West Virginia: Am. Assoc. Petroleum Geologists Bull., vol. 27, no. 9, 1943.

The second, continuously advocated by David White,[4] emphasizes the progressive increase in deformation usually shown by coal measures when traced from low to higher rank areas, the eastern United States coalfields being usually taken as the type example. White did not consider that rank was directly due to the deformation shown by the faults and folds in the coal measures but rather that deformation and increase in rank are both due to deep seated horizontal thrusts. When these thrusts were relieved by faulting and folding the effective pressure on the coal was reduced. From White's theory it follows that although coal generally increases in rank with increasing intensity of regional deformation, intense local deformation causes local *reduction* in coal rank. White accepted increase in rank with depth but did not state if the gradient is increased or decreased by increasing horizontal thrust. The complex relation between deformation and coal rank postulated by White makes it difficult to apply a quantitative check. Nevertheless the Kent coalfield is so gently folded that there can be no significant difference in the intensity of deformation between centre and margin and White's theory consequently fails to explain the variation in coal rank. Moreover it offers no explanation of the regular change of metamorphic gradient. No difficulties are encountered when the rank of the Kent coal is considered due to depth of burial, provided that past geothermal gradients are considered to have had the same relation to structure as they now have.

The evidence collected by Van Orstrand [5, 6] from the oil fields of the United States shows that at most places isothermal surfaces are tilted in the same direction as the beds, geothermal gradients being steeper above anticlinal axes. In the relatively slightly deformed structures from which the data are taken the relation appears to be independent of the age of the beds and is presumably independent of the time of deformation also. Consequently it is reasonable to expect that it will equally apply to geosynclines before deformation. The cause of these variations is unknown, but the explanations so far proposed apply equally to undeformed geosynclines. The maximum variation in gradient across most of the structure is relatively small, but at Oklahoma City oil wells show the gradient to be doubled in a distance of 80 miles.

A diagrammatic explanation of the development of the coal rank distribution is shown in two stages by Figure 3, the first stage, 3a, showing deepest burial in the late Paleozoic, the second showing Kent coalfield as it is now. Rank distribution is generalized by three equal-rank-lines, representing 50 percent volatile matter ($V_2 = 2.0$), 24 percent volatile matter ($V_2 = 1.5$), and 9 percent volatile matter ($V_2 = 1.0$). The positions of the upper and lower of these lines have been obtained by extrapolation from the gradients. It will be noticed that although the 1.0 rank line is about 1,000 feet below the base of the coal measures for its whole length, the 1.5 bulges up to reach its highest stratigraphic and absolute height at the centre of the syncline. This

[4] White, David, Some problems of the formation of coal: Econ. Geol., vol. 3, pp. 292–318, 1908.

[5] Van Orstrand, C. E., Observed temperatures in the earth's crust, *in* Physics of the earth, Pt. 7, Internal constitution of the earth, pp. 125–141, McGraw-Hill, New York, 1939.

[6] Van Orstrand, C. E., Temperature gradients: Problems of petroleum geology (Sidney Powers memorial volume), pp. 989–1021, Am. Assoc. Petroleum Geologists, 1934.

upward bulge suggests that the syncline has been differentially elevated, the amount of elevation being roughly proportional to but somewhat less than the differences in the maximum depth of burial of the base of the coal measures, the upward movement having tended to turn the original syncline inside out and convert it into an anticline. The upper diagram representing deepest burial is more hypothetical, and depends on correct evaluation of the thickness of the lower rank zones that were eroded from the coalfield. For simplicity the eroded bituminous zone has been considered separately from the sub-bituminous and lower rank zone. Fifty percent volatile matter ($V_2 = 2.0$) has been adopted as a convenient arbitrary upper limit for bituminous coal. The thickness of the eroded high and medium volatile bituminous zone has been determined by extrapolation from the gradients, and increases from 6,000 feet at the present margin to 11,000 feet at the center of the syncline, in accordance with the progressive increase in the value of the gradient in that direction.

The change from peat to sub-bituminous coal is due to progressive squeezing out of moisture, there being little change in volatile content expressed as a percentage of fixed carbon. Moreover rank is directly related to density and inversely related to porosity and moisture content of the enclosing measures. Differences in geothermal gradient may have little effect on any except the final stages of this process of compaction under increasing load, and a constant thickness of these low rank beds has been assumed over the whole of the coalfield. Depth of burial and compaction of sediments have been related by Athy [7] and Hedberg [8] to depth of burial without reference to geothermal gradients, and the depth of total burial of highest rank sub-bituminous coal as inferred from their values does not differ significantly from the 7,000-foot depth determined directly from a bore at Notown near Greymouth, New Zealand. This bore passed without apparent metamorphic break from peat in the surface beds through sub-bituminous coal at 3,000 feet to bottom in high volatile bituminous coal at 7,000 feet. After adding this 3,000 feet the maximum depth of burial of the base of the coal measures becomes 14,000 feet at the centre of the syncline, and 9,000 feet at the north-east margin of the coalfield.

CONCLUSIONS.

Structure and metamorphic gradients suggest that coal rank distribution within the Kent coalfield can be explained as the result of two diastrophic phases:

(1) A geosynclinal phase, during which coal measures and other beds gradually accumulated in a subsiding trough. The progressive rise of the isogeotherms through the beds and the progressive increase in weight of overburden caused each seam to be progressively metamorphosed. Coal

[7] Athy, L. F., Compaction and its effect on local structure: Problems of petroleum geology (Sidney Powers memorial volume), pp. 811–828, Am. Assoc. Petroleum Geologists, 1934.

[8] Hedberg, H. D., The effect of gravitational compaction on the structure of sedimentary rocks: Am. Assoc. Petroleum Geologists Bull., vol. 10, no. 11, 1926.

metamorphism was completed when the isogeotherms reached their highest stratigraphic level.

(2) An orogenic phase during which the geosyncline was differentially elevated. Elevation was proportional to but less than the total subsidence, the upper beds being arched into an anticline and eroded, the top of the Staffordian being made almost horizontal, and the lower beds being made less synclinal.

The angle between equal-rank-surfaces and bedding planes at any place at the present time is determined by the angle between the isogeothermal surfaces and bedding planes in the late geosynclinal phase. During the orogenic phase equal rank surfaces and stratigraphic horizons were both deformed but deformation affected both equally and the intersection angle remained unchanged.

Such regular reversal or partial reversal of geosynclinal subsidence during the following orogenic phase is a common and probably widespread tectonic feature, for which the neutral term "eversion" has been suggested in New Zealand. The degree of eversion varies; on the West Coast of the South Island of New Zealand it has gone a stage further than the Kent coalfield, the bottom of the geosyncline having been differentially elevated so that it now forms an anticlinal mountain range from which the thick overlying Cretaceous and Tertiary sediments have been almost entirely stripped. In the Weald,[9] the nearest English example to the Kent coalfield the degree of eversion is about the same as Kent Coalfield. The lower part is still synclinal but the upper part became anticlinal and has been eroded.

GEOLOGICAL SURVEY,
GREYMOUTH, NEW ZEALAND,
May 18, 1948.

[9] Arkell, W. J.: The Jurassic system in Great Britain, Oxford, Clarendon Press, 1933.

THE BEDDING-REPLACEMENT FLUORSPAR DEPOSITS OF SPAR VALLEY, EAGLE MOUNTAINS, HUDSPETH COUNTY, TEXAS.[1]

ELLIOT GILLERMAN.

ABSTRACT.

The Spar Valley fluorspar district in the Eagle Mountains, Hudspeth County, Texas, is one of the few in the western United States containing bedding-replacement fluorspar deposits. The deposits at Spar Valley resemble the bedding-replacement deposits of the Cave in Rock fluorspar district of southern Illinois. Two distinct deposits, the North and the South ore bodies, are present. The North ore body is larger and has been developed by diamond drilling and mining; the following statements apply chiefly to it.

The fluorspar partly replaces a sequence of three sandy limestones interbedded with four calcareous shales in the lower part of the Edwards limestone of Lower Cretaceous age. The fluoritized beds, which dip 40° SW in conformity with underlying limestone, are overlain by thick impermeable gouge along a bedding-plane fault dipping slightly more than 40° SW. The high-grade beds were derived from the sandy limestones, and the low-grade beds, which contain as much as 28 percent of CaF_2, were formed from the calcareous shales. The selectiveness of replacement by the fluorine-bearing solutions, due to differences in the chemical composition, texture, and degree of brecciation of the original rock, resulted in bedding-replacement deposits of variable fluorite content.

A reduction in volume, which accompanied the replacement, led to the development of many cavities. During the later stages of fluoritization these cavities were lined with fluorite crystals, early fluorite grains were coated and interstices between them were filled, and fluorite veins were formed in the ore beds and the underlying dense limestone.

THE Eagle Mountains are in the southeastern part of Hudspeth County, Texas, about 100 miles southeast of El Paso, and 18 miles southwest of Van Horn, Texas. They constitute an isolated mass rising about 3,000 feet above the surrounding bolson. The highest point, Eagle Peak, lies in the central part of the mountains at an elevation of 7,496 feet. The fluorspar deposits in Spar Valley are on the northeastern side of the mountains at an elevation of 5,500 feet. A graded road leads from the mine and mill in Spar Valley to the Southern Pacific Railroad at Hot Wells, and the Texas and Pacific Railroad and U. S. Highway 80 at Allamoore (Fig. 1).

Fluorspar was first discovered in Spar Valley in 1919, but no extensive mining was undertaken until late in 1943. A mill was built in 1944 and put in operation in 1945. A total of about 9,000 tons of fluorspar was mined

[1] Published by permission of the Director, U. S. Geological Survey, and presented at the 27th Annual Meeting, Society of Economic Geologists, New York, March 1947.

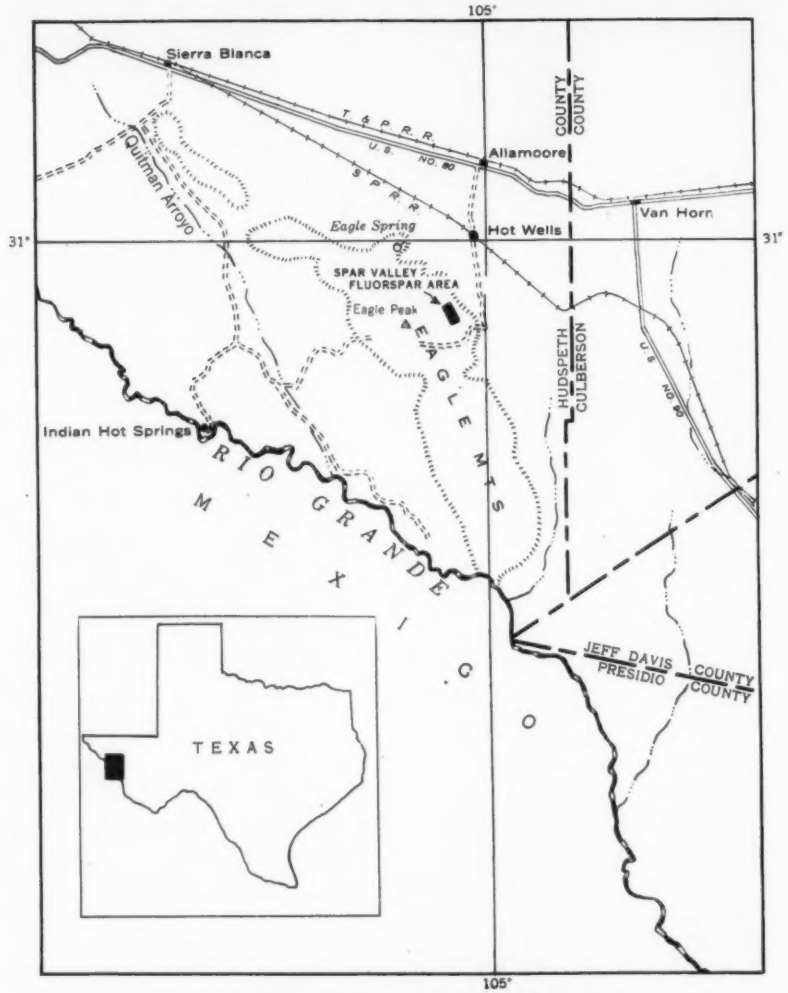


FIG. 1. Map showing location of Spar Valley fluorspar area, Eagle Mountains, Hudspeth County, Texas.

from 1943 to 1947. Other fluorspar deposits in the Eagle Mountains have been found since 1944.

In 1944 studies of the Spar Valley deposits were undertaken by the writer under the direction of H. E. Rothrock, as part of the Geological Survey's program for the investigation of strategic minerals.

GEOLOGY.

The oldest rocks exposed in the area are schists, quartzites, phyllites, and metarhyolites of the Carrizo Mountain schist of Precambrian age. These rocks crop out as small hills in a semicircular area low on the northeast side of the mountains, and are the most southwestern exposures of the Precambrian rocks of the Van Horn Dome.

Permian limestones, 400 to 1,000 feet thick, unconformably overlie the Precambrian metamorphic rocks. A basal conglomerate 20 feet thick is composed almost wholly of pebbles of the metamorphic rocks.

Cretaceous sedimentary rocks lie above the Permian limestones on the northeast side of the Eagle Mountains and extend in an almost unbroken ring around the mountains. The Lower Cretaceous rocks consist of sandstones, shales, limestones, siltstones, conglomerates, and quartzites of the Yucca (of reports), Glen Rose, Cox, Edwards, Kiamichi, and Georgetown formations. The upper Cretaceous rocks consist predominantly of shales, limestones, and sandstones of the Grayson, Buda, and Eagle Ford formations. The presence of many strike faults precludes the measurement of complete sections, but approximately 4,500 feet of Lower Cretaceous sedimentary rocks and 1,800 feet of Upper Cretaceous sedimentary rocks are present in the northern and northeastern parts of the mountains. The sedimentary rocks on the northeastern side of the mountains dip southwest, and those on the southwestern side dip northeast and east. The axis of the large syncline thus formed trends northwest and parallels the axis of the mountains. A thick series of Tertiary volcanic flows and pyroclastics, mainly of rhyolitic and trachytic composition, overlies the sedimentary rocks and constitutes the greater part of the Eagle Mountains. The volcanic rocks, estimated to be at least 3,000 feet thick, have been divided into three groups, as follows: the lower rhyolitic series; trachyte prophyry; and the upper rhyolitic series. The lower rhyolitic series consists of flows, flow breccias, volcanic breccias, and tuffs, mostly rhyolite in composition but becoming trachytic in the upper part. Thin layers of pitchstone and perlite are interbedded with the flow breccias. These rocks of the lower rhyolitic series lie immediately above the sedimentary rocks on both the northeast and southwest side of the mountains and dip in toward the center of the mountains in conformity with the sedimentary rocks. Numerous sills that have invaded the sedimentary rocks are associated with the lower rhyolitic series. The trachyte porphyry overlies the lower rhyolitic series on the northeast side of the mountains but is not present on the southwest side. It is a dark red to purple rock containing prominent phenocrysts of orthoclase in a fine-grained groundmass of orthoclase and a little quartz.[2] The upper rhyolitic series contains less volcanic breccia and tuffaceous material than does the lower rhyolitic series, and the rhyolite is more flinty-looking, denser, and more fractured. Locally the rhyolite tends toward andesite in composition.

A small syenite stock intrudes the volcanic rocks and occupies the central and highest part of the mountains. The rock is medium-grained, brown, and

[2] Thin sections of most of the igneous rocks mentioned in this paper were examined by J. J. Glass, Mineralogist, U. S. Geological Survey.

is composed largely of orthoclase and oligoclase with minor amounts of dark minerals and virtually no quartz. Large orthoclase phenocrysts are prominent. The contacts of the stock are nearly vertical except on the southwest margin where a sill-like protrusion overlies rocks of the upper rhyolitic series. Dikes of rhyolite and dolerite, younger than the Tertiary stock, intrude the earlier rocks.

Alkaline solutions, probably associated with the later stages of the syenite intrusion and with the fluorspar mineralization, have acted upon the volcanic rocks and syenite throughout much of the area, resulting in the albitization of many of the feldspars and the development of quartz and feldspar intergrowths. In some areas the rocks have been so impregnated by the soda-rich solutions that their original nature is unrecognizable.

Faults of several types are common in the area. The earliest faults present are large low-angle thrust faults that preceded the extrusion of the volcanic rocks and the subsequent folding of the area. The thrusting was from the southwest, and the thrusts trend roughly northwest parallel to the strike of the sedimentary rocks. Two distinct thrust faults have been recognized, one of which may belong to a slightly later period, post-dating the folding. A third thrust fault may exist.

High-angle normal and reverse dip faults, trending northeast across the general structure of the Eagle Mountains, are the most common faults in the area. They are found throughout the mountains both in sedimentary and volcanic rocks. As they have not been recognized within the syenite stock, they are believed to antedate this intrusion. Displacements along these faults range from a few feet to hundreds of feet, and some of the larger ones can be traced for more than a mile.

The latest major faults in the Spar Valley area belong to two series, trending northwest and east. The northwest-trending faults cut the sedimentary rocks on both the northeast and southwest sides of the mountains and probably cut the volcanic rocks in the central part of the mountains. They dip at high angles, and stratigraphic displacements of over 1,000 feet have been measured along some of these faults. The east-trending faults are slightly later in age than the northwest-trending faults, although they may have been in part contemporaneous. They are normal faults, characterized by large horizontal displacements, the south side apparently having moved eastward. They dip 60° to 75° S, and extend for miles across the mountains. Wide breccia zones and numerous small subparallel faults are characteristic. Late rhyolite and dolerite dikes are present locally along the fault planes, and quartz and fluorite are common in the brecciated zones. The large east-trending faults acted as the major channelways for the fluorine-bearing solutions during mineralization, and all the fluorspar deposits of the Eagle Mountains are either within these fault zones or in close proximity to them.

FLUORSPAR DEPOSITS.

Fluorspar occurs in the Eagle Mountains as bedding-replacement deposits and as fissure veins. The fluorspar veins are simple space fillings with local

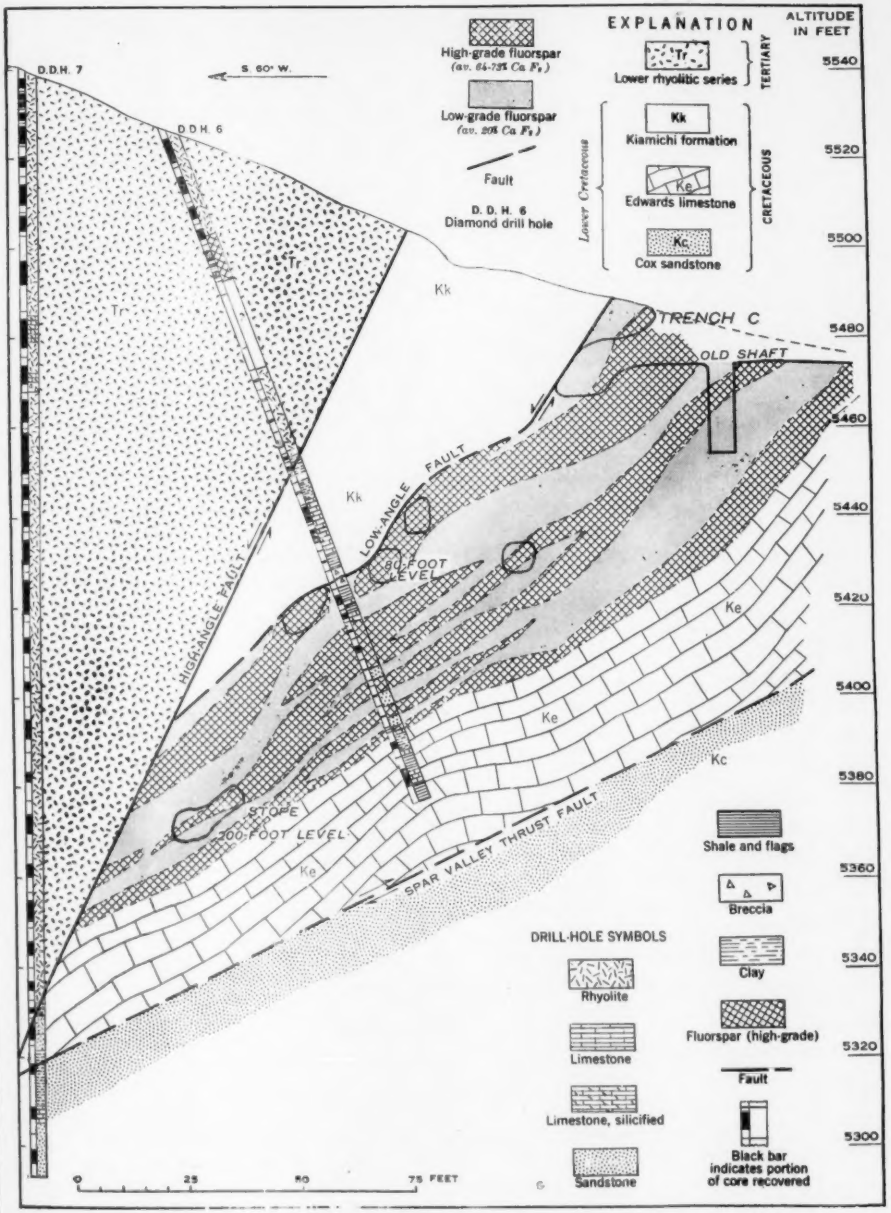


FIG. 2. Cross section through North ore body, 40 feet southeast of the shaft.

replacement of the wall rock and fault breccia, and do not differ greatly from many other fluorspar deposits of this vein type throughout the west. The bedding-replacement deposits, however, are rare in the western part of the United States, and have their closest counterpart in the bedding-replacement deposits of the Cave in Rock fluorspar district of southern Illinois.

The bedding-replacement deposits of Spar Valley are the largest and best known fluorspar deposits in the Eagle Mountains. There are two separate deposits in this area, known as the North ore body and the South ore body. The rest of this paper refers wholly to the North ore body, as it is the larger and has been developed by diamond drilling and by mining. The processes described, however, apply equally well to the South ore body.

The North ore body consists of high-grade beds of fluorspar formed by the replacement of beds of impure limestone, alternating with beds of shale containing small amounts of fluorspar. The ore beds dip 40° to 50° SW in conformity with the country rock and lie immediately above black dense massive limestone of the Edwards limestone of Lower Cretaceous age. They are separated from the shales and flaggy limestones of the overlying Kiamichi formation by as much as 5 feet of clay gouge lying along a low-angle bedding-plane fault that dips essentially parallel to the ore beds. A high-angle normal fault, which dips 60° to 77° SW and is parallel to the strike of the strata, terminates the ore beds 200 feet down the dip of the beds from the collar of the shaft. Rhyolite and volcanic breccia of the lower rhyolitic series are present southwest of the fault (Fig. 2).

Where fully developed, the ore horizon consists of three beds of high-grade fluorspar and four beds of sandy shale containing small amounts of fluorspar, the latter hereafter known as the low-grade beds. Analyses of samples show that the high-grade beds average 64 to 73% CaF_2 and that the low-grade beds average 20% CaF_2.

The ore within the high-grade beds is coarsely crystalline, granular, and porous. The many cavities are lined with large well-formed crystals and clusters of small crystals. Close examination shows that the granular material consists of numerous small sub-cubical crystals of dark green fluorite enveloped by lighter-colored fluorite that partly fills the interstices. Sandy and shaly material is present in the small spaces between the fluorite crystals; where replacement was incomplete some of the original limestone remains as recrystallized calcite. Numerous small fractures and fissures extending through the fluorspar body at right angles to the strike of the beds are filled with veinlets of very high-grade fluorspar. Coarsely crystalline calcite and ankerite of a later generation fill some of the larger cavities, and drusy quartz coats some of the fluorite. The high-grade beds contain some low-grade lenses of sandy shale and friable brown sandstone and isolated blocks of unmineralized dense black limestone.

The low-grade beds consist of gray sandy and clayey shale impregnated with fluorite. Generally the fluorite is too fine-grained to be visible without the aid of hand lens, but some small crystalline masses can be observed. The low-grade lenses within the high-grade beds are similar.

The bedded character of the North ore body is well shown by the alternation of the high-grade and low-grade beds. The contacts of the two are sharp, resulting from the fluorite having selectively replaced beds of different composition and texture. Analyses of the low-grade beds show as much as 28% of CaF_2 as finely crystalline aggregates and veinlets in a sandy and shaly matrix. Very little if any calcareous material remains. Examination of similar shaly beds in the Edwards limestone in nearby localities shows that the beds are somewhat calcareous. The calcareous material in the shaly beds of the ore horizon was attacked by the fluorine-bearing solutions. Since the beds were predominantly shale with only small amounts of $CaCO_3$, the amount of fluorite developed was only a small percentage of the total volume of the beds. As opposed to this, the high-grade beds were originally sandy limestones interbedded with the shale beds; since the initial percentage of $CaCO_3$ was very high, the resultant amount of fluorite was also high. The original limestone was impure, containing some shale and sand that were not replaced. These impurities occur disseminated through the ore and form lenses within the high-grade beds.

As contrasted to the impure limestone and calcareous shale beds which were replaced by the fluorine-bearing solutions, the underlying dense massive relatively pure limestone shows no effects of replacement. The porous nature of the overlying impure beds was a major factor in allowing the entrance of the fluorine-bearing solutions, whereas the impermeable nature of the underlying limestone resulting from the absence of sandy material made it unsuitable for penetration by the mineralizing solutions.

Another factor important in the replacement process, also dependent upon differences in the original texture and composition of the rock, was the effect produced upon the various beds by the widespread pre-mineralization faulting. The dense underlying limestone was merely fractured and faulted along relatively smooth planes, but not extensively shattered. Some of these fractures later acted as channelways for the ascending solutions, but the otherwise impermeable nature and compactness of the rock prevented the solutions from travelling outward from these small openings into the body of the rock. Thus replacement did not occur at this lower horizon. The overlying sandy limestones and shale, however, were the weak beds and were much brecciated and contorted during movement. The shattering and brecciation of the impure limestone increased the facility of penetration of the fluorine-bearing solutions throughout the entire bed. The comparatively uniform grade of the fluorspar throughout the high-grade beds is in part a result of this ease of penetration. The shaly beds yielded by flowage and contortion rather than brecciation. The presence of small amounts of sandy and calcareous material prevented the beds from being entirely impervious to the solutions, but the relative impermeability and the small amount of $CaCO_3$ present resulted in low-grade beds with an uneven distribution of fluorite.

In addition to the texture and chemical composition of the original beds, the structure of the area was an important factor in localizing the ore beds. The important effect of early faulting on the differential permeability of the beds within the ore zone has been described above. The proximity of the

east-trending Rhyolite fault, lying 700 feet north of the shaft in the North ore body and dipping 60° S, is equally important. This fault is one of those that acted as major channelways for the fluorine-bearing solutions. The high-angle fault that terminates the ore body on the 200-foot level, and also the many cross faults and fractures traversing the ore beds, intersect the Rhyolite fault both at depth and along the strike and acted as subsidiary channelways. The presence of the low-angle bedding-plane fault with its thick layer of gouge, immediately overlying the permeable beds, was of great importance in ponding the solutions.

A noteworthy feature of the Spar Valley deposits is the apparent brecciated condition of the fluorspar. This is not due to movement after mineralization. The extensive pre-mineralization faulting in the area had a profound effect upon the replaceable beds, greatly fracturing and brecciating them, and this brecciated structure was preserved during the replacement. Some faulting has occurred after the fluorspar mineralization, but it is of small importance.

A comparison of the textural and structural features of the Spar Valley deposits with the bedding-replacement fluorspar deposits in the Cave in Rock district of southern Illinois shows both differences and similarities. In the Cave in Rock district [3] the finely banded and laminated fluorspar reflects the stratification, crossbedding, and composition of the original limestone. At Spar Valley, finely banded and laminated ore was not found, but the stratification and difference in composition of the original rock are shown on a larger scale by the alternation of the high-grade and low-grade beds. Comb structure, so prevalent in the Cave in Rock district, is not present at Spar Valley, although cavities lined with crystals are common. As one hypothesis for the formation of comb structure in the Cave in Rock district, Currier [4] suggests that it is due to the reduction of volume attending the replacement of calcium carbonate by calcium fluoride, as mentioned previously by Schwerin,[5] followed by the precipitation of additional calcium fluoride in the open spaces thus formed. The progressive replacement of the limestone by the hydrofluoric acid of the mineralizing solutions and the resulting formation of fluorite, would form a cavity that would be filled almost immediately by the precipitation of additional fluorite existing as CaF_2 in the solutions, and thus would result in the building up of crystals from the walls of the progressively forming cavity toward the center. At Spar Valley a similar process of replacement and cavity filling is considered to have taken place, but without the formation of comb structure. It is believed that the fluorine-bearing solutions spread outward from the feeder fractures into the permeable limestones, hydrofluoric acid having easily reacted with the calcium carbonate to form fluorite. The open spaces resulting from the reduction of volume attending this reaction probably were then filled by the precipitation of fluorite existing as CaF_2 in solution and picked up previously by the mineralizing solutions along their paths of travel. This excess CaF_2 coated the fluorite

[3] Currier, L. W., and Hubbert, M. K., Geological and geophysical survey of fluorspar areas in Hardin County, Illinois: U. S. Geol. Survey Bull. 942, pp. 33–36, 1944.

[4] Idem, pp. 37–38.

[5] Schwerin, Martin, An unusual fluorspar deposit: Eng. and Min. Jour., Vol. 126, No. 9, pp. 336–339, 1928.

formed by replacement of the limestone, partly filled the interstices between the earlier fluorite grains, and formed euhedral crystals lining the larger cavities. It also filled the fractures which extend through the ore body at right angles to the strike of the beds and which had been the avenues of access of the solutions. Although having the appearance of a later generation of fluorite, this fissure-filling fluorite actually belongs to the same epoch of mineralization as the replacement fluorite and was deposited, at least in part, simultaneously.

In review, it is believed that at Spar Valley the solutions rose along the east-trending Rhyolite fault, thence along the high-angle fault and the many cross faults and fractures through the quartzites and dense black limestones, and then into the permeable and replaceable, brecciated sandy limestones and contorted shales. The thick gouge of the low-angle fault acted as an effective barrier to further upward movement of the solutions and caused them to spread laterally in the underlying highly permeable beds. The calcareous material was replaced by fluorite, and additional fluorite was deposited from solution in the open spaces apparently formed by the decrease in volume as a result of the replacement process.

U. S. GEOLOGICAL SURVEY,
SILVER CITY, N. M.,
April 27, 1948.

SELECTED BIBLIOGRAPHY

Baker, C. L., Exploratory geology of a part of southwestern trans-Pecos Texas: Univ. of Texas Bull. 2745, 1928.

Baker, C. L., Major structural features of trans-Pecos Texas: in Sellards, E. H., and Baker, C. L., The geology of Texas, vol. II, Structural and economic geology: Univ. of Texas Bull. 3401, pp. 137–214, 1934.

Currier, L. W., and Hubbert, M. K., Geological and geophysical survey of fluorspar areas in Hardin County, Illinois: U. S. Geol. Survey Bull. 942, 1944.

Dennis, W. E., Exploration of Eagle Mountain fluorspar deposits, Hudspeth County, Texas: U. S. Bur. Mines Rept. Inv. 3878, June 1946.

Evans, G. L., Fluorspar deposits in the Eagle Mountains of Hudspeth County, Texas: Univ. of Texas Bur. Econ. Geology, Min. Res. Circ. 26, June 1943.

Gillerman, Elliot, Preliminary report on the Spar Valley fluorspar deposits, Eagle Mountains, Hudspeth County, Texas: U. S. Geol. Survey Strategic Min. Invest. Prelim. Rept. 3–204, 1946.

Schwerin, Martin, An unusual fluorspar deposit: Eng. and Min. Jour., vol. 126, no. 9, pp. 336, 339, 1928.

Sellards, E. H., Adkins, W. S., and Plummer, F. B., The geology of Texas, vol. I, Stratigraphy: Univ. of Texas Bull. 3232, 1932.

Smith, J. F., Jr., Stratigraphy and structure of the Devil Ridge area, Texas: Geol. Soc. America Bull., vol. 51, no. 4, 1940.

DISTRIBUTION OF COASTAL BLACK-SANDS IN NORTH CAROLINA, SOUTH CAROLINA, AND GEORGIA, AS MAPPED FROM AN AIRPLANE.

V. E. McKELVEY AND J. R. BALSLEY, JR.[1]

ABSTRACT.

Black-sand beach concentrates are more widely distributed along the beaches of North Carolina, South Carolina, and Georgia than has been recorded heretofore, as shown by a map prepared by airplane reconnaissance. The map shows also that the black sands diminish in abundance northward, that their distribution is in part related to the configuration of the shoreline, and that they are found only on beaches along the open sea.

BLACK-SAND beach concentrates composed principally of ilmenite, rutile, and zircon are widespread along the south Atlantic coast. Characteristically, the sands are concentrated on the back of the beach by storm waves and are generally best exposed just after a heavy storm; at other times they are concealed in most places by a few inches of light, wind-blown sand.

The best deposits are found in Florida[2] at Amelia Island, Jacksonville Beach, Mineral Beach, Daytona, Eau Gallie, and Melbourne, but others have also been reported farther north along the coast—in Georgia at Tybee, Sapelo Island, and St. Simon Island;[3] in South Carolina at Folly Beach;[4] and in Virginia at scattered localities in the Chesapeake Bay area.[5] Although the general extent of the black sands is thus already known from previous accounts, as far as we know the distribution of the sands has never been mapped.

An opportunity to map the coast-wise distribution of the black sands along part of the coast of North Carolina, South Carolina, and Georgia came unexpectedly to us on a plane trip between Jacksonville, Fla., and Washington, D. C., on the afternoon of April 8, 1945. The plane, a twin-engined Beechcraft piloted by Lt. William Peters, flew along the beach at an altitude of 200 to 300 feet. The black-sand deposits were well exposed (probably as a

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Martens, J. H. C., Beach deposits of ilmenite, zircon, and rutile in Florida: Florida Geol. Survey 19th Ann. Rept., pp. 141–147, 1928; The beaches of Florida: Florida Geol. Survey 21st–22nd Ann. Rept., p. 82, 1931; Beach sands between Charleston, South Carolina, and Miami, Florida: Geol. Soc. America Bull., vol. 46, no. 10, p. 1566, 1935. Vernon, Robert O., Florida mineral industry: Florida Geol. Survey Bull. 24, pp. 139–145, 1943. Phelps, Willard B., Heavy minerals in the beach sands of Florida: Florida Acad. Sci. Proc., vol. 5, pp. 168–172, 1941.

[3] Teas, L. P., Preliminary report on the sand and gravel deposits of Georgia: Georgia Geol. Survey Bull. no. 37, p. 376. Martens, J. H. C., Beach sands between Charleston, South Carolina, and Miami, Florida: Geol. Soc. America Bull., vol. 46, no. 10, p. 1566, 1935.

[4] Martens, J. H. C., Idem, p. 1566.

[5] Gunnell, E. M., and Wilgus, W. L., Minerals from Virginia coastal plain terrace formations: Washington Univ. Studies, new ser. Sci. and Tech. no. 5, pp. 62–67, 1931. Wentworth, C. K., Sand and gravel resources of the coastal plain of Virginia: Virginia Geol. Survey Bull. 32, pp. 100–105, 1930.

result of a strong "northeaster" that had been blowing for the preceding 3 days), and were so clearly visible from the plane that we decided to map their linear distribution, using the U. S. Coast and Geodetic Survey aeronautical charts (scale 1:500,000) as base maps.

The observed distribution of the black sands is shown on Figs. 1–4. We have not had an opportunity to make a detailed analysis of the distribution of the black sands and perhaps the quality of the data does not warrant such an analysis. Nevertheless, several significant facts are apparent:

1. The black-sand concentrates are more widespread than has been recorded heretofore in the literature. Possibly the previously recorded deposits are the most valuable commercially, and certainly many of those shown on the maps will prove valueless. Because much of the coast is accessible only by boat, very likely many of the deposits have not been prospected, however, and the assumption that only the best deposits have been reported does not seem justified.
2. The concentration of black sand diminishes northward. North of Savannah and particularly in the vicinity of Wilmington, we noticed that the concentrates appeared to be thin and narrow, even though persistent in many places.
3. The coast-wise distribution of the black sand seems to be related to the configuration of the shoreline. The south Atlantic coast consists of a series of scallops separated or cut by inlets or river mouths. Characteristically the best concentrations occur at or near the south ends of the scallops; at the south ends of the scallops, which are generally rounded rather than sharp, the concentrates extend nearly to the inlet, but at the north ends, which are generally pointed, the concentrates do not extend to the inlets and are generally best developed just south of the points. This relation was observed at numerous places from the plane (for example, at St. Simon Island, Sapelo Island, St. Catherine Island, and Ossabaw Island, Ga.; Hilton Head Island, on the islands east of St. Helena Island, Kiawah Island, Bulls Island, and Cape Romain, S. C.; and between the mouth of the Santee River, S. C., and the mouth of the Cape Fear River, N. C.). Unfortunately this relationship is not clearly shown on the accompanying maps (their scale is too small to portray adequately the configuration of the shore line) and can be seen much more clearly by plotting the data on the 1:80,000 charts of the U. S. Coast and Geodetic Survey (Nos. 1234 to 1242).
4. As might be expected, the concentrates are only found on the beaches along the open sea.

Because of the way in which the map was prepared, its value is limited in several ways. Its reliability is dependent upon the validity of the assumption that the black color of the beach was black sand and not something else, such as oil or peat. This assumption seems justified because the black sand has a metallic appearance that serves to distinguish it, especially at a distance of 200 feet, from organic deposits. Assuming the black color to have been black sand, only those deposits that were exposed at the surface could be mapped. Naturally no observations were made as to the heavy-mineral content, width, or thickness of the deposits. Inasmuch as surficial black-sand concentrates shift around with every storm, it is worth noting too that the map shows the observed distribution of the black sands on the afternoon of April 8th, 1945.

These limitations are inherent in any map prepared by this method. Even with limitations, the method recommends itself for reconnaissance studies of this type. In addition to heavy concentrates, other shore features,

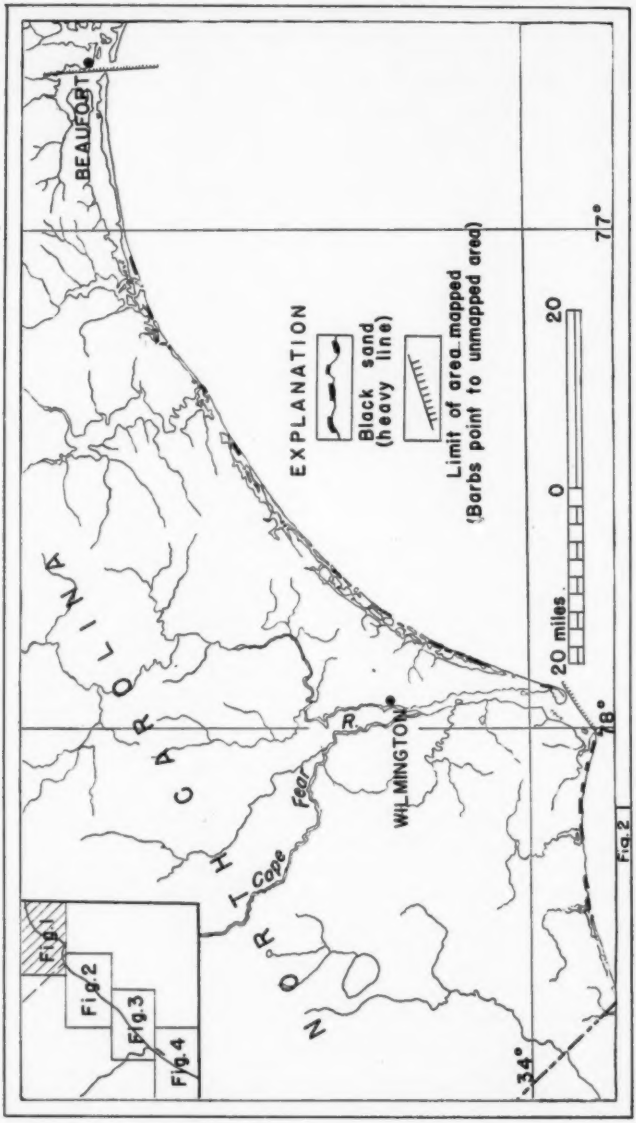


FIG. 1. Distribution of black-sands along part of the coast of North Carolina.

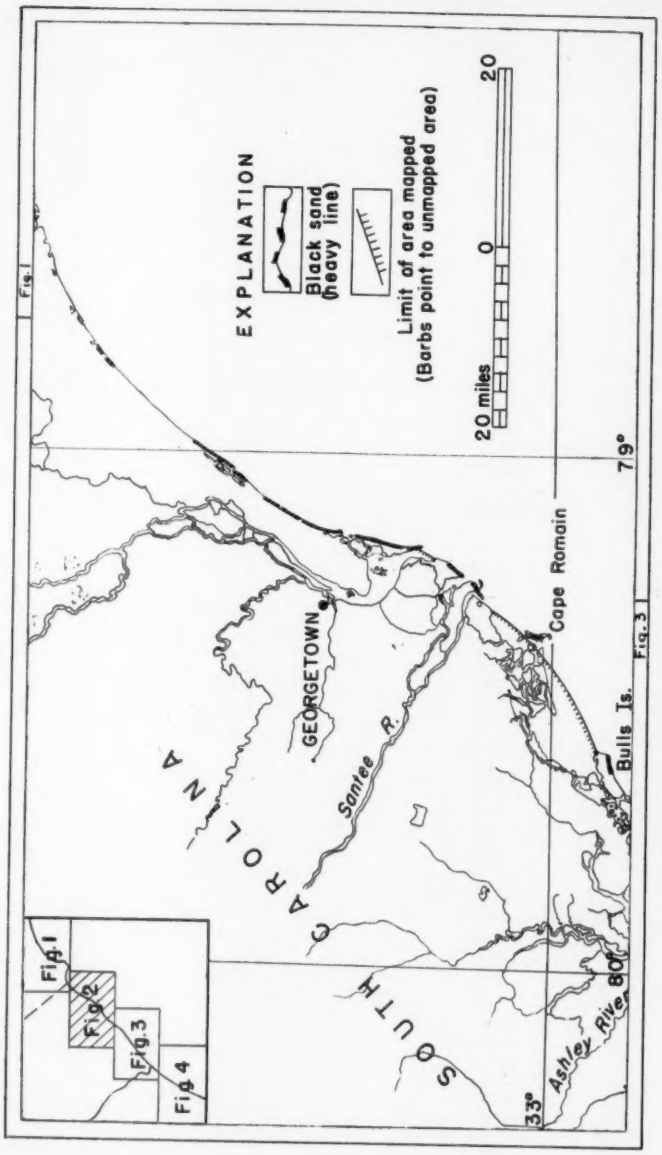


FIG. 2. Distribution of black-sands along part of the coast of South Carolina.

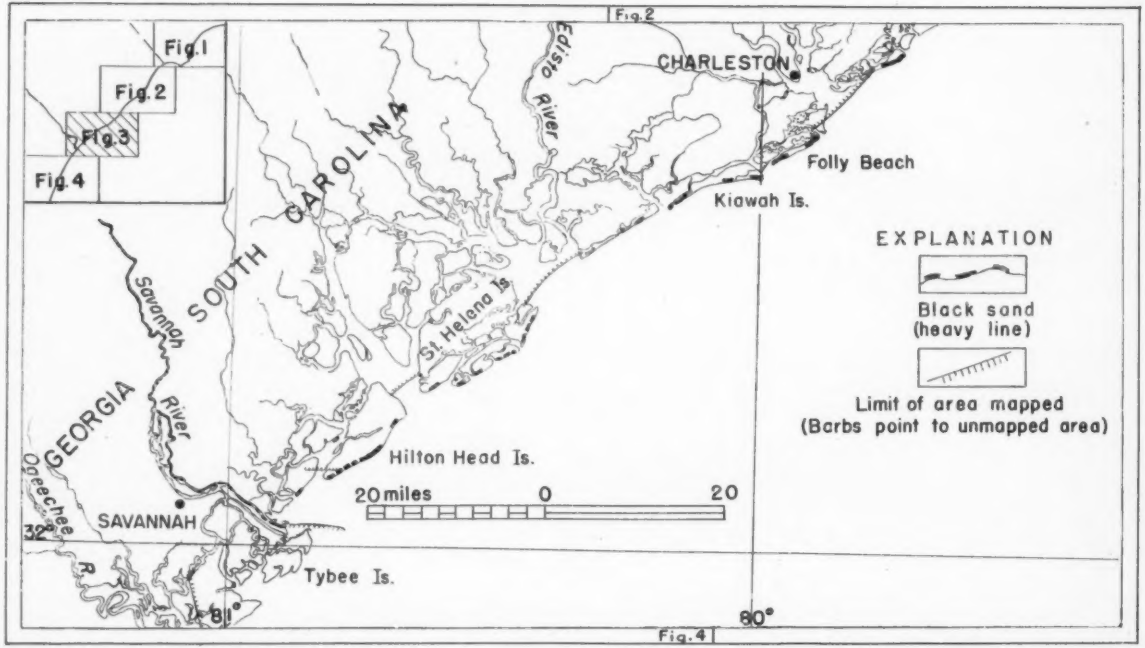


FIG. 3. Distribution of black-sands along part of the coast of South Carolina and Georgia.

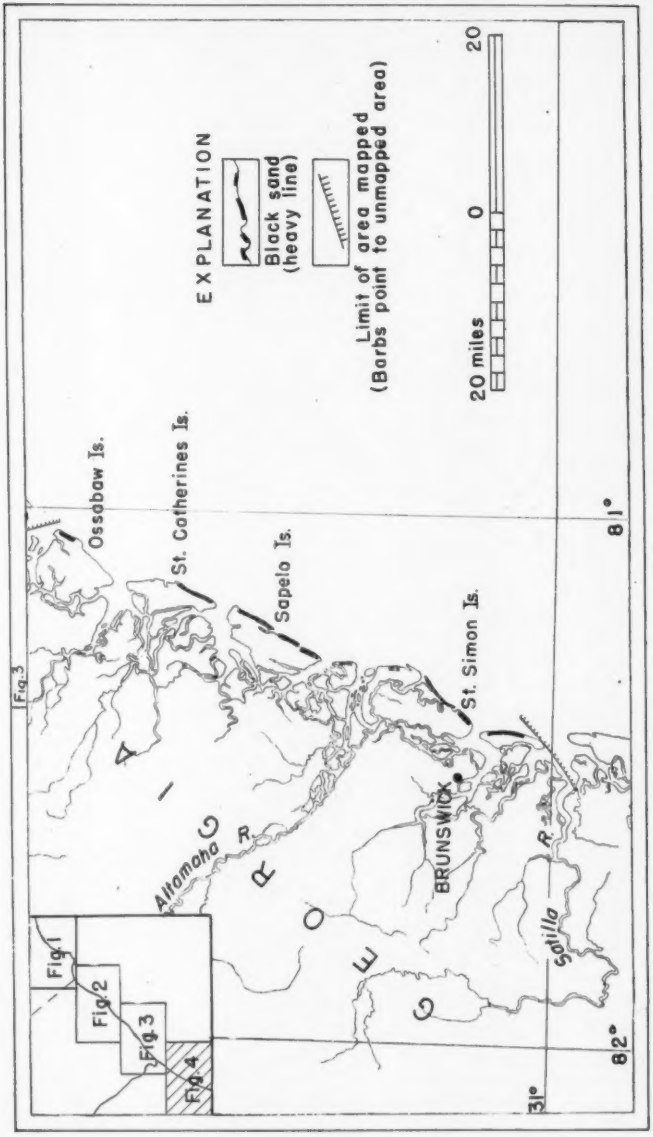


FIG. 4. Distribution of black-sands along part of the coast of Georgia.

such as presence or absence of wave-cut platforms and cliffs, and general size of the beach materials, can be mapped in the same way. Boulders, cobbles, sand, and mud can be easily differentiated when flying at low altitude. Better results could probably be obtained if the beach were photographed in 35-mm color film, using the new Sonne Strip camera with the gyroscopically controlled optical system developed by Mr. Homer Jensen of the Naval Ordnance Laboratory. In this way many of the observations could be checked, and in addition other information (such as width of beach) could be obtained.

Airplane reconnaissance of this type makes possible regional mapping that has not been carried on extensively in the past because of its high cost in time and money when done by other methods. Such mapping ought to yield much information of value in the study of shoreline features and processes.

U. S. GEOLOGICAL SURVEY,
SPOKANE, WASH.,
April 13, 1948.

DISCUSSION AND COMMUNICATIONS

MINERAL RELATIONSHIPS IN THE ORES OF PACHUCA AND REAL DEL MONTE, HIDALGO, MEXICO.

Sir: In June–July number of this Journal Dr. Edward Wisser has commented at considerable length on my paper under the above title that appeared in the January–February number. I too have paced and climbed through so many miles of underground mine workings and tramped over so many square miles of surface that I am well aware that every available line of evidence must be considered if the mining geologist is to be a successful advisor to mine operators and at the same time advance the general knowledge of ore occurrence and genesis. The major *structural* relations of ore deposits are particularly important in the finding of ore and it is fortunate that in recent years more than the usual attention has been devoted to these features. Dr. Wisser has been one of the leaders in such studies and has not only been a keen observer but also a thoughtful interpreter. Such studies are the essential foundation for the understanding of the geology of any mining district. They are *not* however all that is required.

The importance of microscopic studies of ores both in thin sections and in polished surfaces has been so often demonstrated that it is certainly no longer necessary to elaborate upon it. These methods have become not merely an interesting accessory but a major aid in identifying the minerals of the ores and in determining their paragenesis—all essential to a diagnosis of origin. In the old and historic Pachuca District mining on an important scale has ceased with the recent withdrawal of the U. S. Smelting, Refining and Mining Co. from further operations. If this does not mean the end of mining in the district it means a long hiatus during which the collecting of suitable specimens, even of the leaner ores, for microscopic study would be impossible. The writer offers no apologies, therefore, for seizing an opportunity to study the microscopy of the representative collection of Pachuca ores in the U. S. National Museum, many of them of a richness not obtainable in recent years. His purpose was not to interpret the whole geologic picture "through a keyhole" but to contribute a hitherto missing and he believes a useful item to that picture. Whenever practicable the microscopic studies should preferably be carried on by the same persons who conduct the field work. When this is not possible and the ores of a district are not too varied, as in the case of the Pachuca and Real del Monte districts, the laboratory studies of the ores may be carried out by others with valuable results.

EDSON S. BASTIN.

ITHACA, N. Y.
July 22, 1948.

REVIEWS

Geological Structures and Maps. By A. ROBERTS. Pp. 66; figs. 30; maps and exercises 39. Sir Isaac Pitman and Sons, Ltd., London, 1947. Price, $2.50.

This book is planned for a practical course in the interpretation of geologic maps for mining and civil engineers and consists of a series of graded exercises in geologic mapping to provide facility in their interpretation, and to illustrate the more important simple structures by block diagrams. The amount of text matter is subordinate to diagrams. The book should serve well the purpose for which it is planned.

Louis Agassiz, Scientist and Teacher. By JAMES DAVID TELLER. Pp. 145. Graduate School Studies, Education Series, No. 2. The Ohio State University Press, Columbus, Ohio, 1947. Price, $1.50.

All geologists are interested in the life of Louis Agassiz and the study of the effect of his great personality and vigor on the development of research and teaching can well be reappraised after the 100 years that have elapsed since his landing in America.

This new evaluation of Agassiz and his influence in "Back to Nature" is approached from the standpoint of an American University teacher and it is Agassiz' influence as a teacher that is stressed in the seven chapters of this book. They are: The Education of a Naturalist; The Teaching Naturalist; The Educational Activities of Agassiz; The Manner and Method of Agassiz' Teaching; Agassiz and the University Spirit in America; Agassiz and the Museum in America; Agassiz and the Summer School in America.

This is a well written scholarly publication that all students of geology should read, and the paper cover and low price makes it accessible to everyone.

Petrography and Petrology of South African Clays. By V. L. BOSAZZA. Pp. 313; figs. 15. Privately Published. V. L. Bosazza, 39 Barkly Road, Parktown, Johannesburg, 1948. Price, £2 2s.

This bound mimeograph doctoral dissertation is more than a report on clays of a single country. It is a study of clays in general with relation to South African clays. Its 21 chapters cover the character, geochemistry, size distribution, mineral analyses, clay reactions, means of microscopic examination, various methods of classification, sedimentation, and problems of origin.

A great amount of material has been brought together with care and discrimination, and an extensive bibliography is covered. The book should serve as one of the good references on clays and methods of study of clays.

Handbook of Chemistry and Physics. 30th Edit. CHARLES D. HODGMAN, Editor in Chief. Pp. 2686. Chemical Rubber Publishing Co., Cleveland, Ohio, 1948. Price, $6.00.

Through its 30 editions this book continues to be the best known of all handbooks since it covers not only physics and chemistry, but is an indispensable ref-

erence for all engineers, geologists, mathematicians, manufacturers and numerous research laboratories. Like its predecessors it has advanced in size and quality. One hundred pages of tables have been revised and 40 new pages added. Newer data on nuclear physics have been added and a very complete bibliography is included. This enlarged and revised edition will be welcomed by all users.

Mineral Resources of Colorado. Prepared under supervision of JOHN W. VANDERWILT. Pp. 547; pls. 34; figs. 10. Colorado Mineral Resources Board, Denver, Colo., 1948. Price, $2.50.

This extensive work is prepared as an aid to help stimulate increased activity in the mining industry of Colorado. It should serve this purpose.

The report is divided into three parts: Part I, Metals, Non-Metals and Fuels, by John W. Vanderwilt, is largely selections from published reports supplemented by unpublished data. Following a description of the general geology of Colorado, gold, silver, copper, lead and zinc are considered by county with district subdivisions. This is followed by miscellaneous metals, non-metals, nonmetallic minerals, coal, petroleum and oil shale.

Part II, Summaries of Mining Districts and Mineral Deposits, was prepared by the U. S. Geological Survey under supervision of W. S. Burbank. It summarizes published and unpublished geologic studies made by geologists of the U. S. Geological Survey in cooperation with Colorado organizations. This part covers the main individual mining districts of Colorado under individual authors, mostly by those who did the original work. A final section is embraced under Vanadium, Fluorspar and Pegmatites rather than by districts.

Part III, Investigations of Strategic Mineral Resources, by W. M. Traver, Jr., is a summary of investigations made by the Bureau of Mines and describes the government projects and findings in the many districts investigated.

The report serves to bring together under one cover summary data of the geology of practically all mineral deposits of Colorado and this feature alone makes it a valuable reference to have.

BOOKS RECEIVED.

ALAN T. BRODERICK.

U. S. Department of the Interior—Geological Survey Water-Supply Papers.

968-B. Floods of the Puyallup and Chehalis River Basins, Washington. IRVING E. ANDERSON. Pp. 69; figs. 20; pl. 1; tbls. 21. Washington, 1948. *Comparison of precipitation and runoff in two topographically distinct basins shows that flood runoff is influenced more by precipitation than by topographic differences.*

999. Ground-Water Resources of the Cincinnati Area, Butler and Hamilton Counties, Ohio. FRED H. KLAER, JR., AND DAVID G. THOMPSON. Pp. 168; pls. 15; figs. 22. Washington, 1948. *Principal source is in Illinoian drift-filled valleys. Water level is declining.*

1022. Quality of Surface Waters of the United States, 1944. WATER RESOURCES BRANCH. Pp. 311. Washington, 1947. *Water analyses indicating suitability for industrial, agricultural and domestic use.*

1046. Texas Floods of 1940. SETH D. BREEDING. Pp. 91; pls. 7; figs. 12; tbls. 6. Washington, 1948.

1047. Public Water Supplies in Eastern Texas. R. W. SUNDSTROM, W. W. HASTINGS, AND W. L. BROADHURST. Pp. 285; fig. 1; numerous tables. Washington, 1948.

1048. Discharge and Sediment Loads in the Boise River Drainage Basin, Idaho, 1939–40. S. K. LOVE AND P. C. BENEDICT. Pp. 150; pls. 12; figs. 23. Washington, 1948.

Bureau of Mines—Reports of Investigations. Washington, March 1948

4208. Titanium Minerals in Trail Ridge, Fla. ROBERT V. SPENCER. Pp. 21; figs. 19; tbls. 2. *Results of drive-pipe drilling, sampling, and testing a stabilized dune area in northeast Florida. Ilmenite, rutile, zircon were concentrated by mid-Pleistocene shore action.*

4214. Antler Copper-Zinc Deposit, Mohave County, Ariz. T. M. ROMSLO. Pp. 14; tbls. 3; figs. 9. *Zn, Cu, Pb ore as replacements and fillings along fissures in Precambrian schists. Geologic plans and sections.*

4251. Investigation of Arkansas Bauxite. Vol. 1. M. C. MALAMPHY, G. K. DALE, T. M. ROMSLO, A. H. REED, JR., A. OLLAR, AND J. I. TRACEY, JR. Pp. 63; tbls. 12; figs. 31. *Report on one of the Bureau's more important projects. History, production, reserves, exploration and development methods, general and local geology, laboratory procedures, bibliography of the Arkansas bauxite deposits.*

4252 and 4253. Investigation of Arkansas Bauxite. M. C. MALAMPHY, G. K. DALE, T. M. ROMSLO, A. H. REED, JR., AND A. OLLAR. **Vol. 2.** Pp. 16; figs. 3; drill hole logs. **Vol. 3.** Pp. 85; figs. 6; drill hole logs. *Factual data obtained during project, i.e. holes drilled and deposits developed.*

Kansas Geological Survey. Lawrence, 1948.

Bull. 71. Ground-Water Resources of the Kansas City, Kansas, Area. V. C. FISHEL. Pp. 109; pls. 3; figs. 12; tbls. 9.

Bull. 76, Part 1. Graphic Representation of Oil-Field Brines in Kansas. RUSSELL M. JEFFORDS. Pp. 12; figs. 6. *Reasonably accurate estimates of Na, Ca, Mg, dissolved solids can be made from density only.*

Bull. 76, Part 2. Contamination of Deep Water Wells in Southeastern Kansas. CHARLES C. WILLIAMS. Pp. 15; figs. 3; tbls. 3. *Highly mineralized waters from strata overlying aquifers corrode well casings. Methods of detecting such contamination and corrective measures (grouting) described.*

Bull. 76, Part 3. The Occurrence of Corals in Late Paleozoic Rocks of Kansas. RUSSELL M. JEFFORDS. Pp. 23; tbls. 2; figs. 3; pls. 4.

Preliminary Cross Section No. 6. Subsurface Geologic Section from Baca County to Yuma County, Colorado. JOHN C. MAHER. Pp. 11. *Correlation chart of Paleozoic rocks based on microscopic examination of cuttings, electric logs of 8 rotary holes. Composite section; horizontal scale 1″ = 6 mi, vertical scale 1″ = 200′.*

Illionois Geological Survey. Urbana, 1948.

Circ. 140. Covering Old and New Ground. M. M. LEIGHTON. Pp. 7. *Text of radio address at Big Horn Basin Geologic Field Conference.*

Circ. 141. Long-Term Manufacturing Opportunities in the Upper Mississippi Valley. WALTER H. VOSKUIL. Pp. 31; tbls. 20; maps 9; charts 7.

Circ. 142. The Educational Extension Program of the Illinois State Geological Survey. GILBERT O. RAASCH. Pp. 4.

Geology and Ore Deposits of Red River and Twining Districts, Taos County, New Mexico. A Preliminary Report. CHARLES F. PARK, JR., AND PHILIP F. MCKINLAY. Pp. 35; figs. 7. New Mexico Bureau of Mines and Mineral Resources, Circ. 18. Socorro, 1948. *Large areas of hydrothermally-altered Precambrian to Cenozoic rocks associated with minor Au, Cu, Mo deposits in veins, breccias and shear zones.*

Ohio Geological Survey. Columbus, 1947.

Inf. Circ. 4. Generalized Section of Rocks of Ohio. WILBER STOUT. *Detailed stratigraphy chart.*

Rept. Inv. 3. Areal Extent and Thickness of the Salt Deposits of Ohio. JAMES F. PEPPER. Pp. 14; figs. 3. *Salina formation. Maps show salt thickness and depth in Ohio.*

Oregon Department of Geology and Mineral Industries. Portland, 1947.

Bull. 35. Geology of the Dallas and Valsetz Quadrangles, Oregon. EWART M. BALDWIN. Pp. 61; pls. 7; figs. 2. Two colored geologic maps, $12 \times 17''$, $1'' = 1$ mile. *Eocene, Oligocene volcanics and sediments.*

Bull. 36. Five Papers on Foraminifera from the Tertiary of Western Oregon. JOSEPH A. CUSHMAN AND ROSCOE E. AND KATHERINE C. STEWART. Pp. 110; figs. 4; pls. 13.

The Geology of Nashville, Tennessee. CHARLES W. WILSON, JR. Pp. 172; figs. 29. Tennessee Division of Geology Bull. 53. Nashville, 1948.

Coal in South America. THOMAS FRASER. Pp. 16; table 1; figs. 3. Pan American Institute of Mining Engineering and Geology, United States Section, Tech. Paper 6. New York, 1948.

Nomininge and Sicotte Map-Areas, Labelle and Gatineau Counties. E. AUBERT DE LA RÜE. Pp. 62; pls. 8; 2 colored geol. maps, $1'' = 1$ mile. Quebec Department of Mines Geol. Rept. 23. Quebec, 1948. *Grenville rocks intruded by numerous igneous bodies. Traces of metallic and non-metallic ore minerals.*

Biography of the Earth. GEORGE GAMOW. Pp. 194; figs. 62; pls. 22. New American Library. New York, 1948. Price, 35 cts. *Age and birth of the earth, constitution, mountains, evolution of continents, climates of the past, life on the earth; popular style.*

Great Britain Department of Scientific and Industrial Reaserch. London, 1948.

The South of Scotland. J. PRINGLE. Pp. 87; figs. 14; pls. 7. *Ordovician to Cenozoic stratigraphy, paleontology, structure. Pleistocene to present history.*

The Welsh Borderland. R. W. POCOCK AND T. H. WHITEHEAD. Pp. 83; pls. 11; figs. 39. *Precambrian to Triassic stratigraphy, paleontology, structure. Pleistocene to present history.*

Borehole Temperatures in the Transvaal and Orange Free State. L. J. KRIGE. Pp. 12; tbls. 11. Union of South Africa Department of Mines, Geol. Ser. Bull. 18. Pretoria, 1948. *Deepest hole, 7,504 ft., 38.8° C; hottest hole 47.2° C at 7,000 ft.*

Hyderabad Geological Survey.

Geol. Ser. Bull. 2. A Brief Outline of the Geological History of Hyderabad State with Special Reference to its Mineral Resources. KHURSHID MIRZA. Pp. 107; numerous tables; geol. map, 1″ = 32 miles. Hyderabad-Deccan, 1943.

Geol. Ser. Bull. 4. A Preliminary Note on the Iron Ore Resources of the Hyderabad State. KHURSHID MIRZA. Pp. 16; geol. map, 1″ = 16 miles. Hyderabad-Deccan, 1940.

Geol. Ser. Bull. 5. A Note on the Occurrence of Mica in Hyderabad State. KHURSHID MIRZA. Pp. 24; tbl. 1. Hyderabad-Deccan, 1943.

Jour. Vol. IV, Pt. 1. Pp. 188; pls. 11; colored geol. map, 1″ = 4 miles. Hyderabad-Deccan, 1941. *Four papers on geology of parts of Gulbarga and Mahbubnagar.*

Jour. Vol. IV, Pt. 2. Pp. 103; numerous maps, figures, tables. Hyderabad-Deccan, 1945. *10 separate short papers on geologic subjects.*

Jour. Vol. V, Pt. 1. Pp. 182; pls. 8; 2 geol. maps, 1″ = 4 miles. Hyderabad-Deccan, 1947. *6 papers on geology of parts of the Gulbarga, Mahbubnagar and Nalgonda districts.*

SCIENTIFIC NOTES AND NEWS

L. R. LAUDON, chairman of the Department of Geology, University of Kansas, GEORGE P. WOOLLARD, Guggenheim Fellow at Woods Hole and Lecturer in Geophysics at Princeton University, and SHELDON JUDSON, who recently was granted his doctorate in geomorphology at Harvard University, have all joined the staff of the Department of Geology, University of Wisconsin.

T. A. RICKARD has been made an Honorary Member of the Institution of Mining and Metallurgy, London, "in recognition of his long and valued service to the mining and metallurgical profession and to the Institution."

WILLIAM B. NELSON is employed as a mining geologist for the Cía. Minera de Guatemala, at Coban, Atta Verapaz, Guatemala.

JAMES C. DUDLEY has acted as geologist with Cía. Minera Venturosa, S. A., of Chihuahua, Mexico, since last June.

R. B. SPRAGUE, who returned to the States last September after working for the Cerro de Pasco Copper Corporation, has taken a job as geologist with the American Smelting and Refining Company, Salt Lake City.

PHILIP W. CHASE has been made manager of explorations for the Oliver Iron Mining Co., Duluth. He directs investigations and exploratory work throughout the world in search of raw materials such as iron ore and manganese.

OLIVER BOWLES has been appointed a part-time research professor in the department of geography of the University of Maryland, where he will supervise certain studies in co-operation with the Bureau of Mines concerning mineral resources of the world.

MICHEL LEGRAYE (Stanford '23), professor of Economic Geology at the University of Liège, Belgium, has been elected vice-president of the new Institut pour la Recherche Scientifique en Afrique Centrale.

RALPH W. STONE, Pennsylvania State Geologist (retired), is the new president of the National Speleological Society.

HARRISON SCHMITT has resigned his position as manager of the geological and exploration work in the Southwest for The New Jersey Zinc Company (Empire Zinc Company) to accept the appointment as a consultant on geological work and mineral appraisals for the same company. Mr. Schmitt will continue to give some time to general consulting practice.

AUSTIN EDWARDS of Australia, author of the recent book "Textures of the Ore Minerals," was a recent visitor in the United States and at New Haven, Conn.

J. WILLIS AMBROSE, formerly on the staff of the Geological Survey of Canada, and for the past year Consulting Geologist in Toronto and Special Lecturer in geology at Queen's University, Kingston, Ontario, has been appointed Professor of Geology at that institution.

SAMUEL GOLDICH of the Texas Bureau of Economic Geology and the United States Geological Survey has accepted a position as Associate Professor of Petrography and Petrology in the Department of Geology at the University of Minnesota. He will fill the position vacated by the retirement of Dr. F. F. Grout. Dr. Goldich assumed his duties on September 15th.

The Division of Geology of the Indiana Department of Conservation is installing a spectrographic laboratory at Indiana University at Bloomington under the direction of Richard K. Leininger, formerly of the Research Laboratories of the Armco Steel Corporation at Middletown, Ohio. In addition to various applications in research, the laboratory will furnish analytical data on limestone, dolomite, sand, gravel, clay, coal ash, and other non-metallic raw materials. The first program of analysis will include limestones and dolomites of Indiana. Two field parties began systematic sampling of the active quarries of the State during the summer of 1947 and will complete the field portion of the project during the field season of 1948.

WILLIAM T. HOLSER has been appointed as assistant professor in mineralogy and petrology at Cornell University. He worked this summer with the U. S. Geological Survey, Section of Mineral Deposits, on contact-metamorphic beryllium in Texas and elsewhere.

W. C. STOLL was appointed in 1947 by the Argentine government to make economic geologic studies of the mining districts of the Republic, under the jurisdiction of the Secretariat of Industry and Commerce. Dr. Stoll was formerly associated with the U. S. Geological Survey and later with the Cía. Aramayo de Mines en Bolivia.

GARRETT A. MUILENBURG is severing his connection with Missouri School of Mines after thirty-two years of continuous service. His plans for future activities are still incomplete.

FRANK F. GROUT, Professor of Geology and Mineralogy at the University of Minnesota, retired July 1st, 1948. As a retirement gift, his students, colleagues and friends presented him with a cash purse to defray his expenses to the International Geological Congress that convened in London this summer.

THOMAS G. MURDOCK, of Raleigh, N. C., formerly Assistant State Geologist of North Carolina, and with the Foreign Economic Administration missions in Brazil, Ethiopia, and Italy during the war, has been commissioned a Reserve Officer in the Foreign Service of the United States and assigned to Elizabethville, Belgian Congo, as Consular Attaché.

WILLIAM JAMES BICHAN, Director of Mineral Resources for the Province of Saskatchewan, has returned to the Regina head office from an examination of the new uranium and thorium discovery at Lac La Ronge, Saskatchewan, made by Government aided prospectors in May, 1948.

HUGH E. MCKINSTRY sustained a broken leg in July while doing field work in Shasta County, California.

E. C. ANDREWS, Government Geologist of the State of New South Wales from 1920 to 1932 and for many years Associate Editor of Economic Geology, died on July 1st.

The U. S. Department of the Interior has advised the U. S. Atomic Energy Commission that in accordance with a request from the Commission it has approved an order withdrawing from entry and reserving for use of the AEC approximately 115 square miles of public land in Southwestern Colorado and Southeastern Utah. During this summer the Commission, with the cooperation of the U. S. Geological Survey, has made a comprehensive study of these areas and tested by diamond drilling for uranium-bearing ores. Lands found to contain no uranium will be released from the withdrawal orders and will again be open for entry. It is expected that in furtherance of AEC policy the lands found to contain uranium will become available for development and mining by private interests under arrangement with the Government.

Lev. A. Mekler, petroleum engineer and technologist, has been appointed as a part-time consultant for the Stanford Research Institute, Calif., and will retain his office in Chicago.

The new Rock-color Chart is now available and can be purchased from the Division of Geology and Geography, National Research Council, Washington 25, D. C., for $5.50 per copy. This chart is designed especially for field use but is suitable also for use in the office or laboratory. It consists of 8 sheets, 5 by 7½ inches, and will fit conveniently in the back of a field notebook. It includes 115 colors which indicate the range of rock colors for all purposes, and a brief text explains the systems used for the chart arrangement and the color names. The form and arrangement are based on the Munsell system and the color names have been taken from the ISCC–NBS system as described in National Bureau of Standards Research Paper RP 1239. Also, the Munsell numerical designation is placed under each color for the use of those geologists who wish to make fine color distinctions. The base chart was printed by the Government Printing Office and the color chips have been hand colored and stuck on the charts by the Munsell Color Co. of Baltimore, Md. The colors are as permanent as possible, and the red, yellow and brown ranges have been used successfully on the Soil Color Names Charts of the Department of Agriculture for nearly 10 years. The Rock-color Chart was prepared by the Rock-color Chart Committee representing the following organizations: E. N. Goddard, Chairman, U. S. Geological Survey, Parker D. Trask, G.S.A., Ronald K. De Ford, A.A.P.G., Olaf N. Rove, S.E.G., Joseph T. Singewald, Jr., and R. M. Overbeck, Ass. of Amer. State Geologists. This committee was made a subcommittee of the Committee on Symposium on Sedimentation, Division of Geology and Geography of the National Research Council.

Some time ago a specially outfitted Douglas transport plane landed at Lourenco Marques, Portuguese East Africa, to begin aerial mapping and an airborne magnetometer survey in a search for new oil resources there over a concession area of 45,000 square miles. Aero Service Corporation of Philadelphia is making the survey for the Mozambique-Gulf Oil Co. Existing African maps being inadequate, precise aerial maps will be made and be used first to guide the plane in the airborne magnetometer survey of the area, then the maps will be used later for the oil company's development planning. The airborne magnetometer used is a new oil exploration tool, developed by the Gulf Research and Development Co. The airborne magnetometer should perform magnetic reconnaissance of the African Survey area at the rate of 150 miles per hour, and aerial mapping will be done at the same speed. About six to twelve months will be required to complete the aerial mapping and magnetometer survey by the staff of 15 men. Aero Service recently completed the first large-scale airborne magnetometer survey ever performed, mapping some 85,000 square miles in the Bahamas.

The Industrial and Mineral Industries Conference was held in Oklahoma City, October 12–13, combining the Mineral Industries Conference of the Oklahoma Geological Survey and the Industrial Conference, as originally sponsored by the Tulsa Chamber of Commerce.

VANNEVAR BUSH, chairman of the Research and Development Board, National Military Establishment, announces the formation of a Special Committee on Technical Information to promote effective exchange of research and development information among the departments of the National Military Establishment. The committee will study the problem of collecting, correlating, reproducing and disseminating technical information potentially useful in the research and development program of the National Military Establishment. Study and application of new methods and techniques to the problem of technical information organization, and promotion of active research in this effort, are expected to receive special attention by the group. At the first meeting of the committee, Dr. Detlev W. Bronk, chairman, pointed out the desirability of applying scientific methods to utilize more effectively the large body of information created by scientific activity. Dr. Bronk, recently appointed president of Johns Hopkins University, is also chairman of the National Research Council and Foreign Secretary of the National Academy of Sciences.

VICTOR C. HEIKES, formerly with the U. S. Geological Survey, died at the age of 81 in Carmel, Calif., on June 29.

The U. S. Atomic Energy Commission has appointed EVAN FRANK WILSON of Akron, Ohio, as assistant director of the Division of Raw Materials. Mr. Wilson will be responsible for the research program of the Division of Raw Materials which is concerned principally with the development of methods of extracting uranium from low grade domestic sources. He will have his headquarters at the Commission's New York Office of Directed Operations, 70 Columbus Avenue, New York, N. Y.

NEIL CAMPBELL, geologist with the Consolidated Mining and Smelting Co. of Canada in the Yellowknife area of the Northwest Territories, was awarded the Barlow Medal of the Canadian Institute of Mining and Metallurgy for his paper, "The West Bay Fault at Yellowknife," which, in the opinion of the judges, was "the best paper on a geological subject submitted to the Institute during the year 1947."

ABBOTT CHARLES, former assistant geologist at the Sullivan mine of the Consolidated Mining and Smelting Co. of Canada, is now at Lark, Utah, with the U. S. Smelting, Refining and Mining Co.

A. HENRY FRETZ, who has taught geology at Lehigh for the last thirty years, retired on June 30.